Dissertation Defense

Computational Fluid Dynamics Uncertainty Analysis for Payload Fairing Spacecraft Environmental Control Systems

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Agenda

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Agenda

- Chapter 5: Computational Fluid Dynamics Uncertainty Analysis
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  - ECS System Experimental Comparison
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Chapter 1: Introduction

Motivation

Research Goals

Motivation

- Spacecraft components may be damaged due to airflow produced by Environmental Control Systems (ECS).
- Spacecraft must survive both pre-launch and launch environments
- ECS Systems supply air to keep spacecraft cool, dry, clean while on the ground
- Delicate spacecraft instruments are sensitive to high velocity flow from ECS system
  - Manufactures set Impingement Requirements
- (2) Methods to Verify Requirements
  - Test vs. CFD

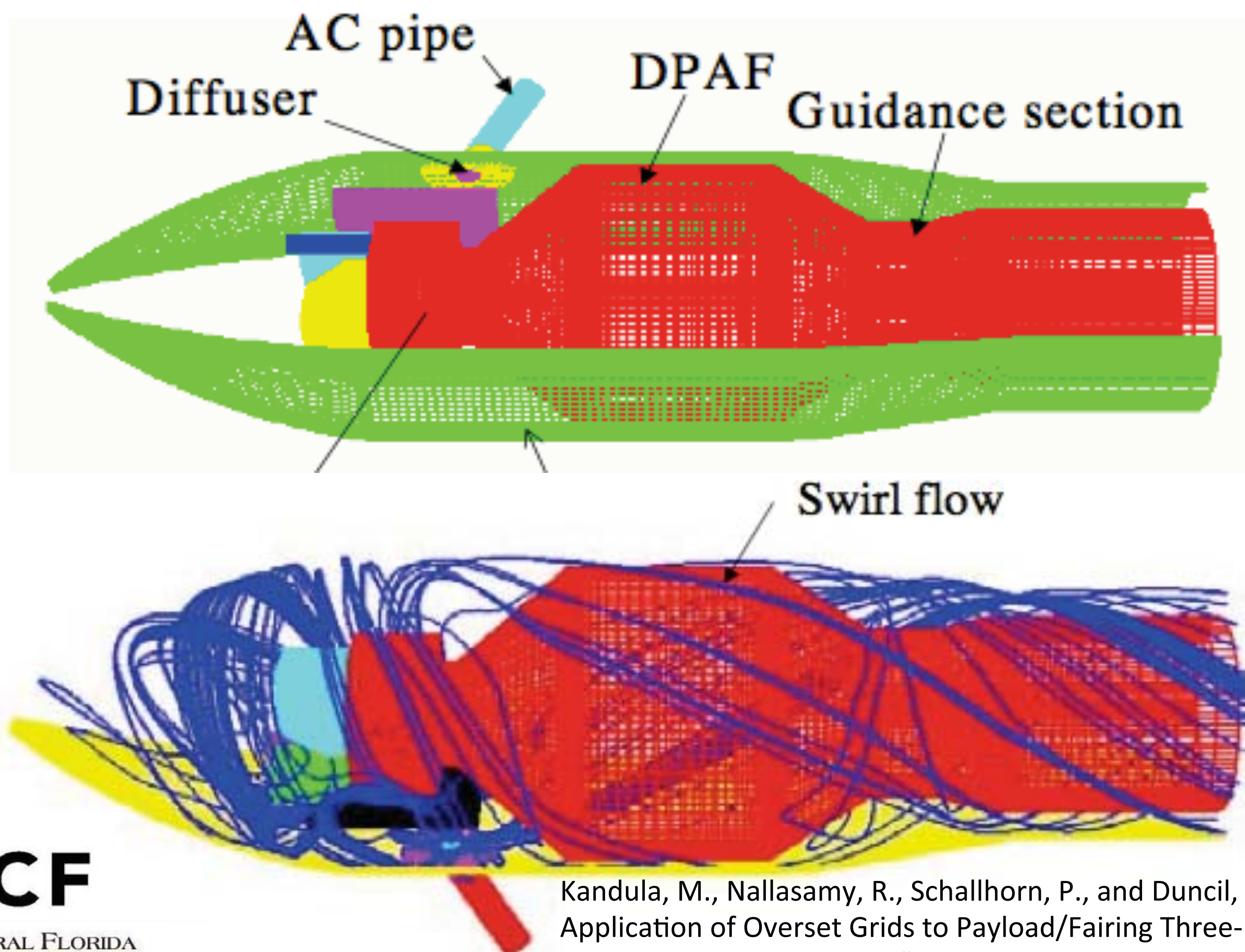
Motivation: ECS System Overview

- Environmental Control System
  - Prior to launch, cold air (air conditioning) flows downward around the spacecraft after it has been encapsulated in the Payload Fairing.
  - The cold air is delivered through an air-conditioning (AC) pipe, which intersects the fairing and flows past a diffuser located at the pipe/fairing interface
  - After passing over the spacecraft, it is finally discharged through vents
  - The Payload Fairing air conditioning is cut off at lift off.

Kandula, M., Nallasamy, R., Schallhorn, P., and Duncil, L., "An Application of Overset Grids to Payload/Fairing Three-Dimensional Internal Flow CFD Analysis," AIAA-2002-3253, 2005, KSC-2007-215.

Motivation: ECS System Overview

- Example of ECS CFD Analysis



Kandula, M., Nallasamy, R., Schallhorn, P., and Duncil, L., "An Application of Overset Grids to Payload/Fairing Three-Dimensional Internal Flow CFD Analysis," AIAA-2002-3253, 2005, KSC-2007-215.

Motivation: ECS System Overview

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- Example of an ECS system airflow test

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Kandula, M., Hammad, K., and Schallhorn, P., "CFD Validation with LDV Test Data for Payload/Fairing Internal Flow," AIAA-2005-4910, KSC-2005-4910.

Motivation: Problem

- Computational Fluid Dynamics (CFD) is being used without proper validation
- "There can be no validation without experimental data with which to compare the results of the simulation" – Coleman and Stern
- Experimental Data is expensive
  - Shrinking Budgets
- Pairing experimental data, uncertainty analysis, and analytical predictions provides a comprehensive approach to verification and is the current state of the art. (ASME V&V 20-2009)
- <u>A method is sought to conservatively envelop the exact solution using CFD only</u>
  - Without Experimental Data

Motivation: NASA-STD-7009

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STANDARD FOR MODELS AND SIMULATIONS

Requirement 4.4.7 & 4.4.8

- Shall document any uncertainty quantification processes used for:
- Shall document any quantified uncertainties, both physical and numerical, for:
  a. The referent data
  b. The input data
  c. The Modeling and Simulation (M&S) results
  d. The propagation of uncertainties
  e. The quantities derived from M&S results

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Research Goals

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1. Demonstrate a CFD Uncertainty Analysis for 3-D, low speed, incompressible, highly turbulent, internal flow can be calculated for an entire simulation domain
2. Investigate a higher order interpolation scheme to be used for grid interpolations and uncertainty quantification
3. Investigate the applicability of using the ASME 5-Step procedure for the entire computational domain to estimate numerical uncertainties.
4. Calculate the uncertainty in using different turbulent models.
5. Demonstrate this method can contribute to the study of importance of input parameters in CFD.
6. Compile a table for uncertainty estimates by input parameter.
7. Demonstrate the ability to use OPENFOAM to calculate the velocity field of an Environmental Control System.
8. Compare the results of OPENFOAM verses an industry standard CFD software program (ie FLUENT and STARCCM+).

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Chapter 2: Literature Review

Summary of Literature Review

Summary of the State of the Art

Uncertainty Analysis

Proposed Methodology without Test Data

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Summary of ASME Standard ASME V&V-20-2009

Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer

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Approach

- Estimate Interval within which δ_{model} falls with a given degree of confidence

$$\delta_{model}\ \varepsilon [E - u_{val}, E + u_{val}]$$

$$E = S - D$$

- Error Sources (U_{num},U_{input},U_D),Uncertainty Equation

$$u_{val} = k\left(\sqrt{{u_{num}}^2 + {u_{input}}^2 + {u_D}^2}\right)$$

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Numerical Uncertainty, U_{num}

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- 5 Step Procedure for Uncertainty Estimation
  - Step 1: Representative Grid Size

$$h_1 = \left(\frac{Total\ Volume}{total\ number\ of\ cells\ in\ fine\ grid}\right)^{\frac{1}{3}}$$

$$h_2 = \left(\frac{Total\ Volume}{total\ number\ of\ cells\ in\ medium\ grid}\right)^{\frac{1}{3}}$$

$$h_3 = \left(\frac{Total\ Volume}{total\ number\ of\ cells\ in\ coarse\ grid}\right)^{\frac{1}{3}}$$

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Numerical Uncertainty, U_{num} (continued)

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– Step 2: Select 3 significantly (r>1.3) different grid sizes

$$r_{21} = \frac{h_2}{h_1}$$

$$r_{32} = \frac{h_3}{h_2}$$

– Use CFD Simulation to analyze key variables, Sk

$$\varepsilon_{21} = S_{k2} - S_{k1}$$

$$\varepsilon_{32} = S_{k3} - S_{k2}$$

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Numerical Uncertainty, U_{num} (continued)

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– Step 3: Calculate observed order, p

$$p = \left[\frac{1}{\ln(r_{21})}\right] * [\ln\left(\frac{\varepsilon_{32}}{\varepsilon_{21}}\right) + ln\left(\frac{{r_{21}}^{p} - sign\left(\frac{\varepsilon_{32}}{\varepsilon_{21}}\right)}{{r_{32}}^{p} - sign\left(\frac{\varepsilon_{32}}{\varepsilon_{21}}\right)}\right)$$

– Step 4: Calculate extrapolated values

$$S_{ext}{}^{21} = \frac{({r_{21}}^{p} * S_{k1} - S_{k2})}{({r_{21}}^{p} - 1)}$$

$$e_{a}{}^{21} = \frac{(S_{k1} - S_{k2})}{(S_{k1})}$$

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Numerical Uncertainty, U_{num} (continued)

– Step 5: Calculate Fine Grid Convergence Index & Numerical Uncertainty, Factor of Safety, Fs=1.25

$$GCI_{fine}{}^{21} = \frac{1.25 * \ e_a{}^{21}}{(r_{21}{}^{p} - 1)}$$

– Assumption that the distribution is Gaussian about the fine grid, 90% Confidence

$$u_{num} = \frac{GCI_{fine}{}^{21}}{2}$$

Input Uncertainty, U_{input}

- Input error is based on a Taylor Series expansion in parameter space

$$u_{input} = \sqrt{\sum_{i=1}^{n} \left(\frac{\vartheta S}{\vartheta X_i} u_{xi} \right)^2}$$

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Proposed Methodology without Test Data

Without Experimental Data??

Proposed Methodology **conservative estimate to envelop true value

If there is no experimental data, D=0, δ_D=0, and u_D=0.

$E = S - D = S$

$\delta s = S - T$

$E = S - D = T + \delta s - (T + \delta_D) = \delta_S - \delta_D = \delta_S$

$$u_{val} = k\left(\sqrt{u_{num}{}^2 + u_{input}{}^2 + u_D{}^2}\right)$$

$$u_{val} = k\left(\sqrt{u_{num}{}^2 + u_{input}{}^2}\right)$$

Report the simulated result, S as

$$S \pm u_{val}$$

Without Experimental Data -continued

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- Report $S \pm u_s$
- *k – value (Use Student-t Distribution)*
- Treat all input variables as 'random' and run separate CFD case
- Treat as an oscillatory convergence parameter

$$U_{Oscillatory} = \left| \frac{1}{2}(S_U - S_L) \right|$$

Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
9	8	1.86
10	9	1.833
11	10	1.812
12	11	1.796
13	12	1.782
14	13	1.771
15	14	1.761
16	15	1.753
17	16	1.746
18	17	1.74
19	18	1.734
20	19	1.729
21	20	1.725
22	21	1.721
23	22	1.717
24	23	1.714
25	24	1.711
26	25	1.708
27	26	1.706
28	27	1.703
29	28	1.701
30	29	1.699
31	30	1.697
41	40	1.684
51	50	1.676
61	60	1.671
81	80	1.664
101	100	1.66
121	120	1.658
infty	infty	1.645

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Chapter 3: Applying the State of the Art CFD Uncertainty Analysis to a Backward Facing Step

Grid Refinement Study

CFD Uncertainty Analysis of Backward Facing Step

Results and Discussion

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Backward Facing Step Example

AIAA-2013-0258

Velocity Magnitude Prediction – Backward Facing Step

Symmetry

Uniform Velocity Inlet
U = 10 m/s

Pressure Outlet
Pgage = 0

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Uncertainty Variables ke-realizable (OPENFOAM – SimpleFoam)

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- There are 87 Different Input Parameters for the ke-realizable model in SimpleFoam
  - These include:
    - Boundary Conditions
    - Wall Functions
    - Fluid Properties
    - Turbulence Parameters
    - Solution Schemes
    - Solvers
    - Mesh
    - ect.

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Uncertainty Variables Considered

Type of Variable	Variables Xi	Value	Bias Error
Boundary Conditions	epsilion turbulent mixing length dissipation rate inlet (m2/s3)	0.5	0.5
	k turbulent intensity kinetic energy inlet (m2/s2)	0.05	0.05
	pressure outlet (Pa)	101325	2%
	velocity inlet (m/s)	10	0.5
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.79E-06	[13.6e-06 -> 23.06e-06]
Grid Size	Method - Uses Oscillatory Uncertainty	1,192,000 1,862,500 3,311,689	
Numerical	Method - Uses Richardson's Extrapolation (ASME 5 Step Procedure) – Calculated for Velocity at each Cell		
Solver	OpenFOAM (SimpleFoam) vs. Fluent		
Turbulence Models	ke-realiable, kwSST, and SpalartAllmaras		

Expanding the data reduction equation for the listed variables in order from top to bottom.

$$U_{CFD-Velocity} = \left(\left(\left(\frac{\partial V}{\partial e} \right)^2 B_e^2 \right) + \left(\left(\frac{\partial V}{\partial k} \right)^2 B_k^2 \right) + \left(\left(\frac{\partial V}{\partial p} \right)^2 B_p^2 \right) + \left(\left(\frac{\partial V}{\partial U} \right)^2 B_u^2 \right) + \left(\left(\frac{\partial V}{\partial nu} \right)^2 B_{nu}^2 \right) + \left(\left(\frac{\partial V}{\partial g} \right)^2 B_g^2 \right) + \left(\left(\frac{\partial V}{\partial num} \right)^2 B_{num}^2 \right) + \left(\left(\frac{\partial V}{\partial solver} \right)^2 B_{solver}^2 \right) + \left(\left(\frac{\partial V}{\partial turb} \right)^2 B_{turb}^2 \right) \right)^{1/2}$$

Oscillatory Variables

- The uncertainty for each of the following was calculated for each cell using the following method outlined by Stern, Wilson, Coleman, and Paterson. ***S*** is the simulated result. For this case it is the upper velocity S_U and the lower velocity S_L.
  - **epsilion turbulent mixing length dissipation rate inlet (m^2/s^3)**
  - **k turbulent intensity kinetic energy inlet (m^2/s^2)**
  - **Pressure outlet (Pa)**
  - **Velocity Inlet (m/s)**
  - **Kinematic viscosity nu=17.06e-06 [13.6e-06 -> 23.06e-06] (m^2/s) represents air [0-50-100] degrees C**
  - **Grid size**
  - **Turbulence Models**
  - **Solver**

$$U_{Oscillatory} = \frac{1}{2}(S_U - S_L)$$

Results (Oscillatory Variables)

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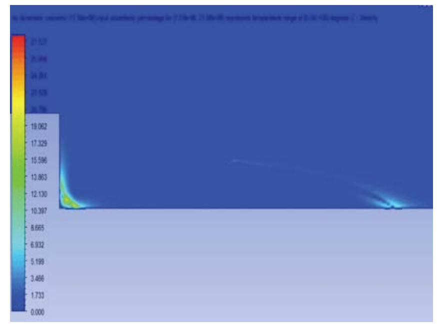
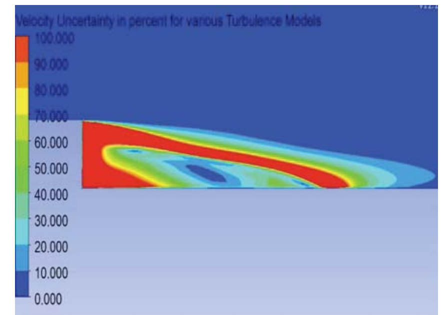
epsilion turbulent mixing length dissipation rate inlet (m^2/s^3)
0 – 1.155 percent

Pressure outlet (Pa)
0 – 20 percent

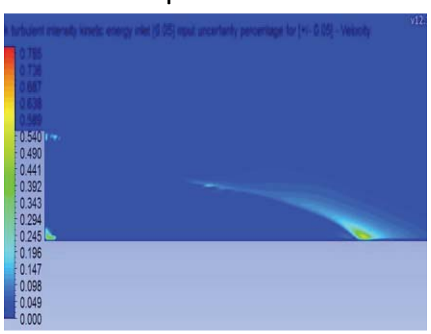
Kinematic viscosity nu=17.06e-06 [13.6e-06 -> 23.06e-06] (m^2/s) represents air [0-50-100] degrees C
0 – 27.727 percent



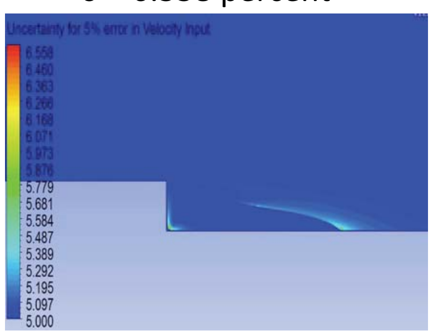
Turbulence Models
> 100 %



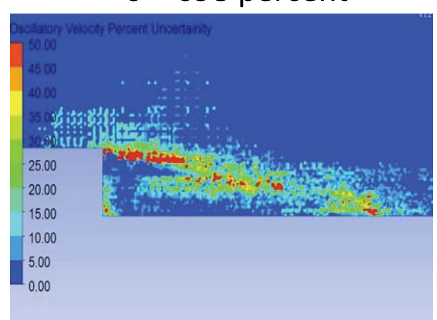
k turbulent intensity kinetic energy inlet (m^2/s^2)
0 – 0.785 percent



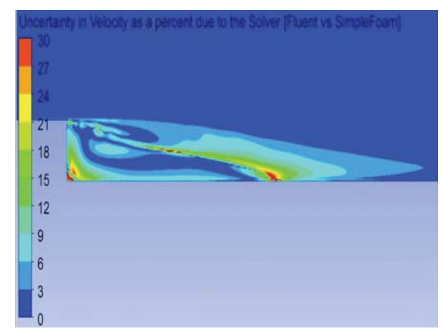
Velocity Inlet (m/s)
0 – 6.558 percent



Grid size
0 – 698 percent



Solver
> 30 %



Percent – is the percentage change in local velocity

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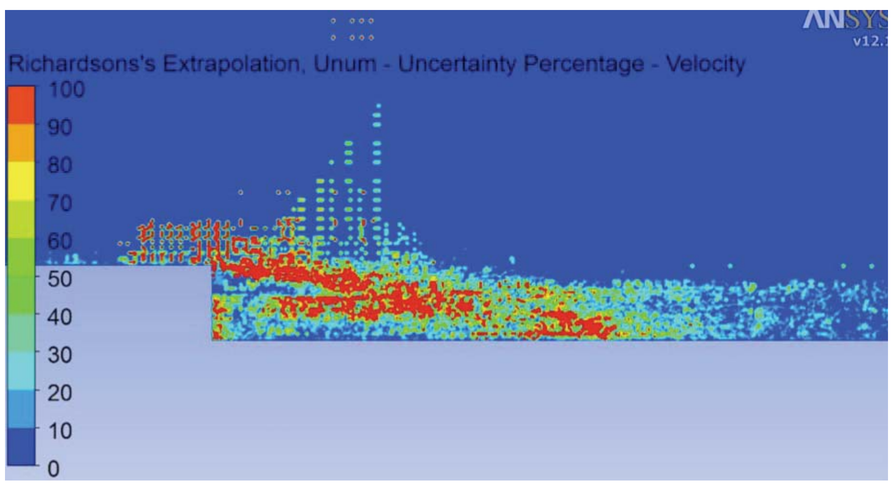
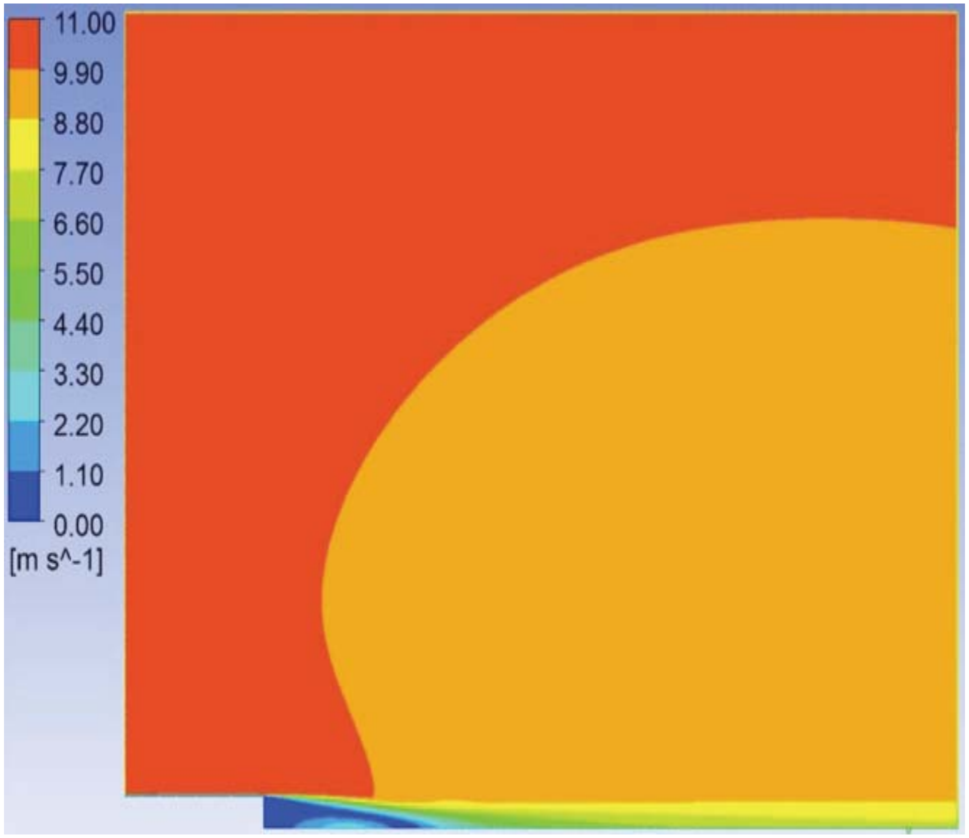
Results (Monotonic Convergence)

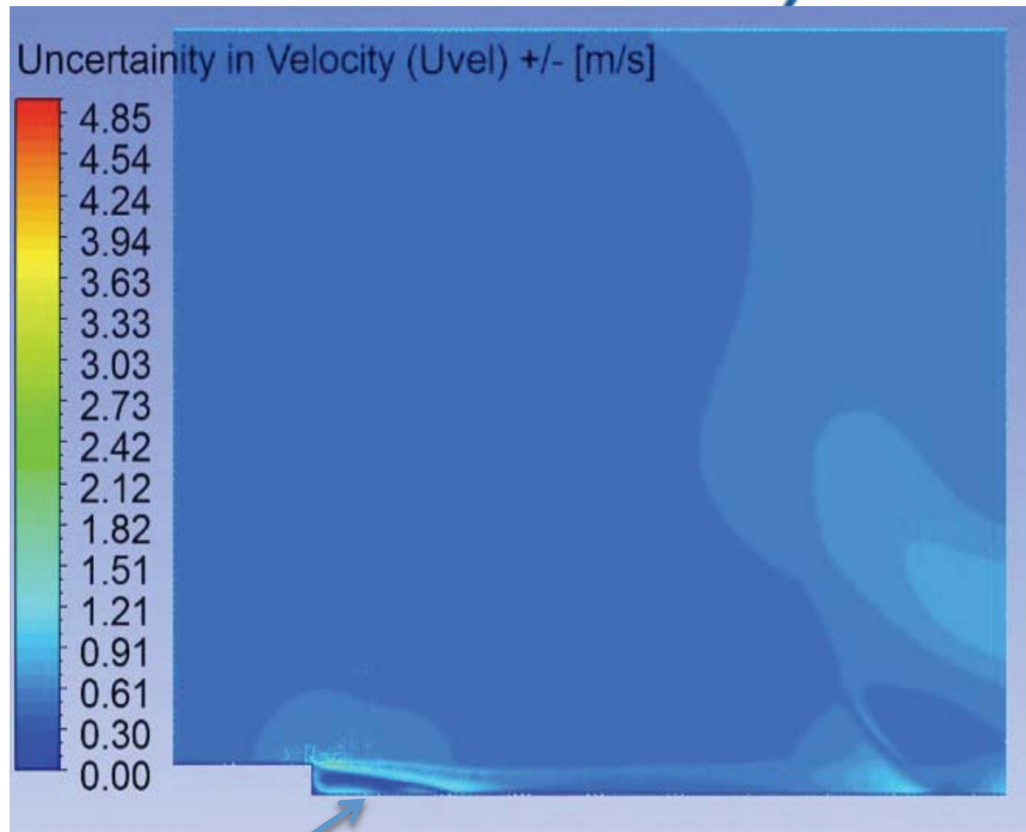
Numerical – ASME V&V-20-2009 5 Step Procedure

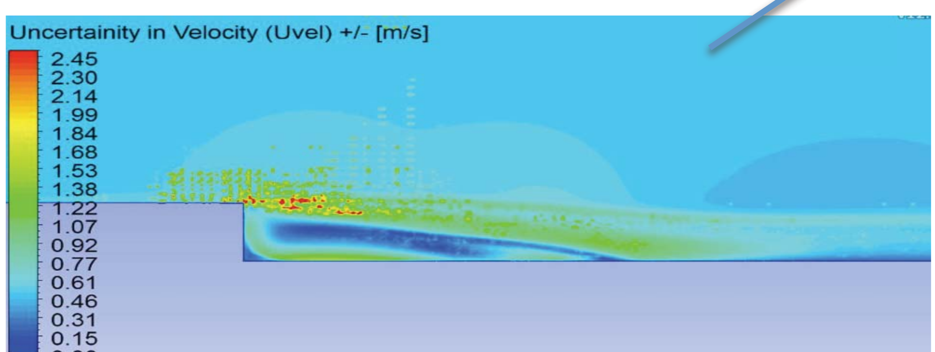
For a grid size of 1,192,000 cells [grid 2 -1,862,500 cells], [grid3 - 3,311,689 cells], the uncertainty in the velocity prediction was 0 – 5300 percent as shown in Figure 11 as estimated by Richardson's extrapolation method.



Velocity Prediction with Uncertainty







The highest uncertainty is +/- 4.85 m/s.

Conclusion of AIAA-2013-0258

- This paper outlines an uncertainty analysis for the ke realizable turbulence model for a backward facing step.
- The velocity magnitude was predicted using CFD.
- The uncertainty parameters listed in the Table were analyzed using an oscillatory convergence calculation or a monotonic convergence calculation.
- Plots of the velocity magnitude can be combined with a corresponding uncertainty plot for an accurate velocity prediction.
- Numerical Uncertainty using ASME 5 Step Procedure produced un-realistic results

Conclusion /Recommendation

- The following input uncertainty's are recommended

Type of Variable	Variables Xi	Value	Bias Error	Uncertainity
Boundary Conditions	epsilion turbulent mixing length dissipation rate inlet (m2/s3)	0.5	0.5	1.2% of local velocity
	k turbulent intensity kinetic energy inlet (m2/s2)	0.05	0.05	0.8 % of local velocity
	pressure outlet (Pa)	101325	2%	10x the variation
	velocity inlet (m/s)	10	0.5	1.3x the variation
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.79E-06	[13.6e-06 -> 23.06e-06]	28% of the local velocity
Grid Size	Method - Uses Oscillatory Uncertainty	1,192,000 1,862,500		grid specific
		3,311,689		
Numerical	Method - Uses Richardson's Extrapolation (ASME 5 Step Procedure) – Calculated for Velocity at each Cell			
Solver	OpenFOAM (SimpleFoam) vs. Fluent			30% of the local velocity
Turbulence Models	ke-realiable, kwSST, and SpalartAllmaras			Future work will consider more turbulence models

Chapter 4: Spacecraft ECS System Overview and Modeling

Publically Available Information on EELV ECS Systems

Modeling and CFD Analysis of (3) Generic Non-proprietary

Environmental Control Systems and Spacecraft Configurations

Spacecraft / ECS System

AIAA-2014-0440

EELV Public Available Information

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- The Rockets Behind the Missions:
  - Delta II
  - Delta IV
  - Atlas V
  - Pegasus
  - Taurus
  - Falcon 9

- http://www.nasa.gov/centers/kennedy/launchingrockets/

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EELV Public Available Information

- Each of these vehicles have a Payload Planners Guide or Users Guide
- http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIIPayloadPlannersGuide2007.pdf
- http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIVPayloadPlannersGuide2007.pdf
- http://www.ulalaunch.com/site/docs/product_cards/guides/AtlasVUsersGuide2010.pdf
- http://www.orbital.com/NewsInfo/Publications/Pegasus_UG.pdf
- http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf
- http://www.spacex.com/Falcon9UsersGuide_2009.pdf

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Delta II

- Air-conditioning is supplied to the spacecraft via an umbilical after the payload fairing is mated to the launch vehicle.
- The payload air-distribution system provides air at the required temperature, relative humidity, and flow rate as measured
- The air-distribution system uses a diffuser on the inlet air-conditioning duct at the fairing interface.
- If required, a deflector can be installed on the inlet to direct the airflow away from sensitive spacecraft components
- The air can be supplied to the payload between a rate of
- 1300 to 1700 scfm.
- Diameter of Fairing is 3meters

http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIIPayloadPlannersGuide2007.pdf

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Delta IV

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- The air is supplied to the payload at a maximum flow rate of 36.3 kg/min to 72.6 kg/min (80 to 160 lb/min) for 4-m fairing launch vehicles and 90.7 kg/min to 136.0 kg/min (200 to 300 lb/min) for 5-m fairing launch vehicles.
- Air flows around the payload and is discharged through vents in the aft end of the fairing.
- Fairing sizes 4meter and 5 meters in diameter

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http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIVPayloadPlannersGuide2007.pdf

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Atlas V

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- Internal ducting defectors in the PLF direct the gas upward to prevent direct impingement on the spacecraft.
- The conditioning gas is vented to the atmosphere through one-way flapper doors below the spacecraft.
- The PLF air distribution system will provide a maximum air flow velocity in all directions of no more than 9.75 mps (32 fps) for the Atlas V 400 and 10.67 mps (35 fps) for the Atlas V 500.
- There will be localized areas of higher flow velocity at, near, or associated with the air conditioning outlet.
- Maximum air flow velocities correspond to maximum inlet mass flow rates.
- Reduced flow velocities are achievable using lower inlet mass flow rates.

- Flow Rates
  - A) Atlas V 400: 0.38–1.21 kg/s ±0.038 kg/s (50–l60 lb/min ±5 lb/min),
  - B) Atlas V 500: 0.38–2.27 kg/s ±0.095 kg/s (50–300 lb/min ±12.5 lb/min)

- Fairing sizes are 4meters and 5 meters in diameter

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http://www.ulalaunch.com/site/docs/product_cards/guides/AtlasVUsersGuide2010.pdf

Pegasus

- The fairing is continuously purged with filtered air.
- The flowrate of air through the fairing is maintained between 50 and 200 cfm.
- The air flow enters the fairing forward of the payload and exits aft of the payload. There are baffles on the inlet that minimize the impingement velocity of the air on the payload.
- Fairing diameter is 0.97 meters

http://www.orbital.com/NewsInfo/Publications/Pegasus_UG.pdf

Taurus

- Upon encapsulation within the fairing and for the remainder of ground operations, the payload environment will be maintained by the Taurus Environmental Control System (ECS).
- Fairing inlet conditions are selected by the Customer
- Fairing diameters are 63 inches and 92 inches

http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf

Falcon 9

- Once fully encapsulated and horizontal, the Environmental Control System (ECS) is connected
- Payload environments during various processing phases are:
  - In hanger, encapsulated – Flow Rate: 1,000 cfm
  - During rollout: 1,000 cfm
  - On pad: Variable from 1000 to 4500 cfm
- Fairing diameter is 5.2 meters

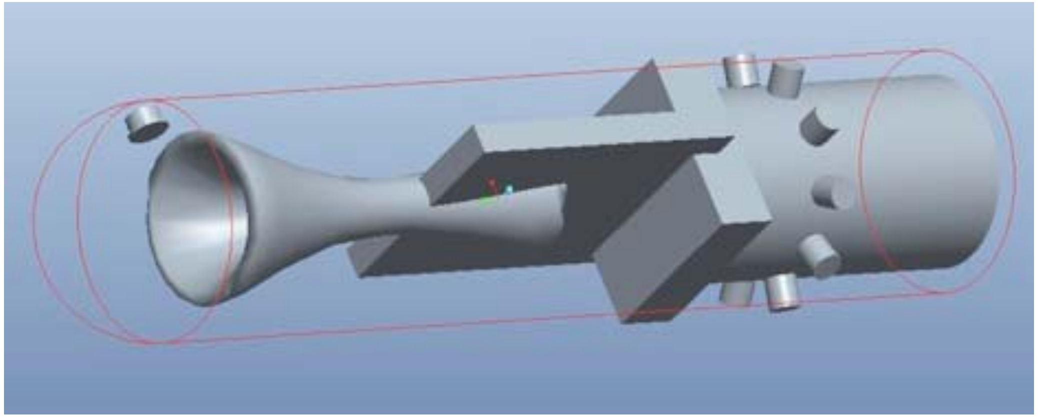
http://www.spacex.com/Falcon9UsersGuide_2009.pdf

(3) Configurations

- Fairing Sizes are approximately 1m, 1.6m, 2.3m, 3m, 4m, 5m in diameter.
- (3) generic fairing diameters are selected to envelop the EELV fairing configurations
  - 0.75m
  - 3.5 m
  - 5.5 m
- Inlet Conditions range from 1000 cfm to 4500 cfm
- Spacecraft diameters range with fairing sizes, a generic spacecraft was drawn and scaled accordingly

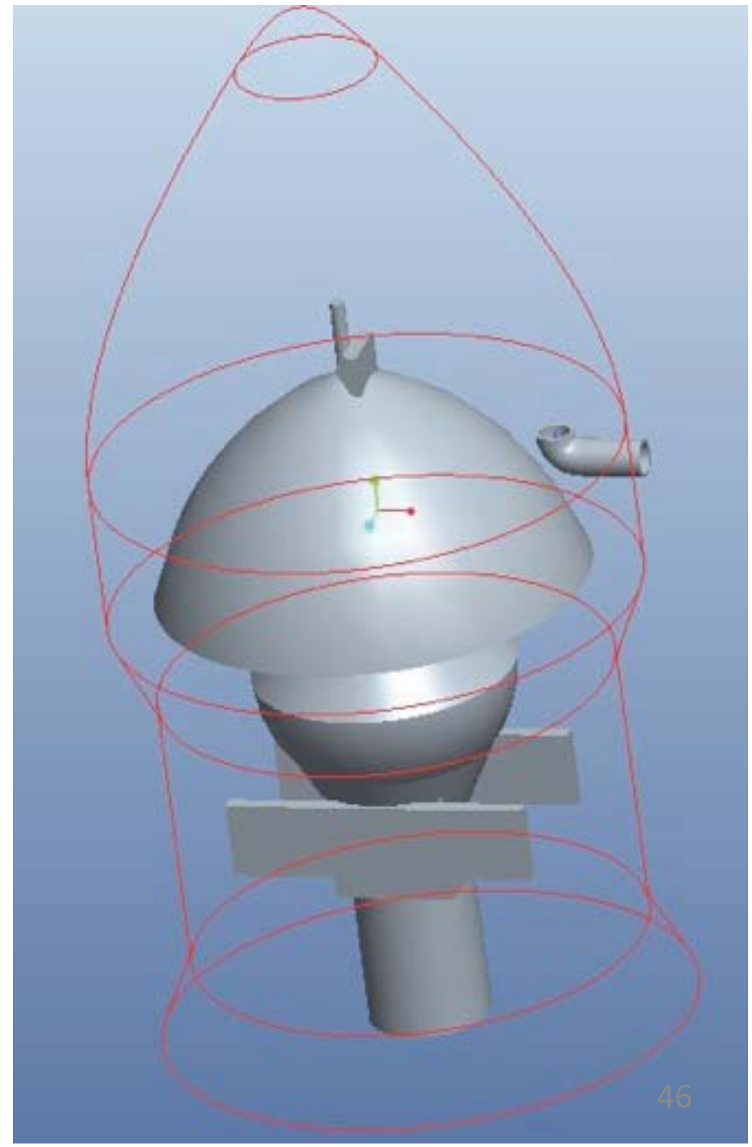
(3) Configurations

- CAD model of the spacecraft was created in Pro/ENGINEER, 0.75m



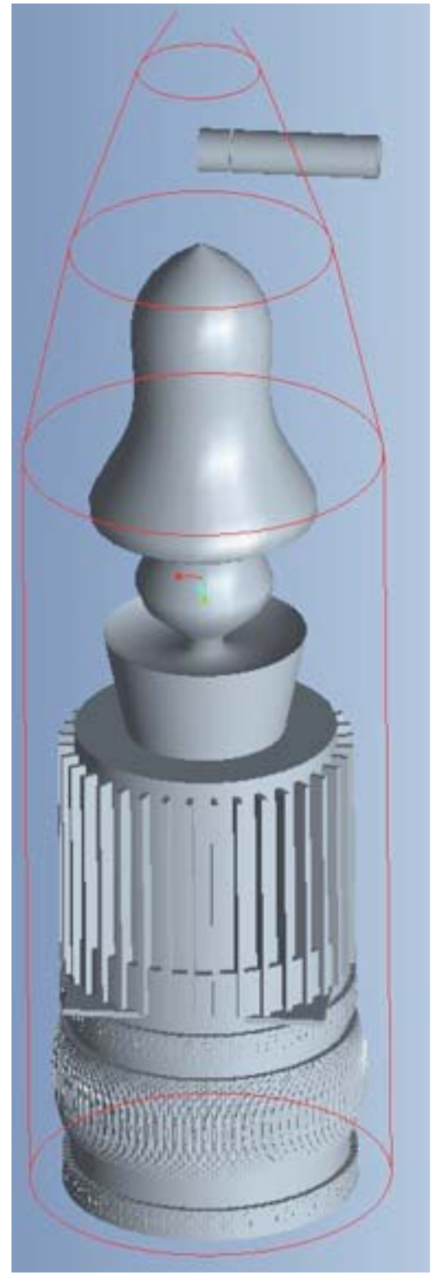
(3) Configurations

- 3.5m



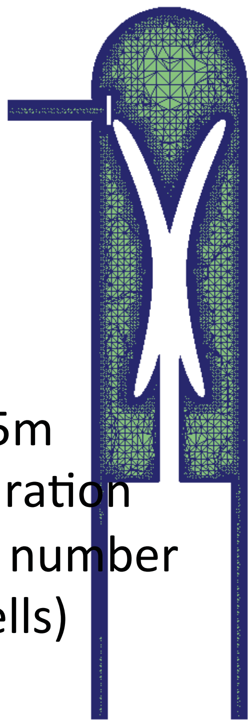
(3) Configurations

- 5.5m

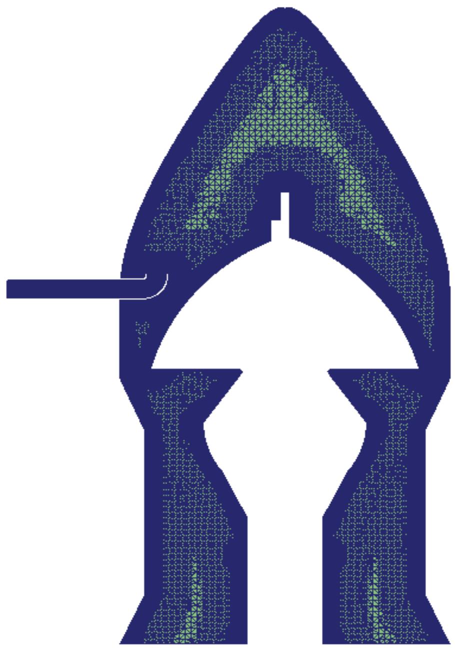


CFD Modeling

- Snappy Hex – Mesher



0.75m Configuration (6762865 number of cells)



3.5m Configuration (8594480 number of cells)

5.5m Configuration (6980673number of cells)

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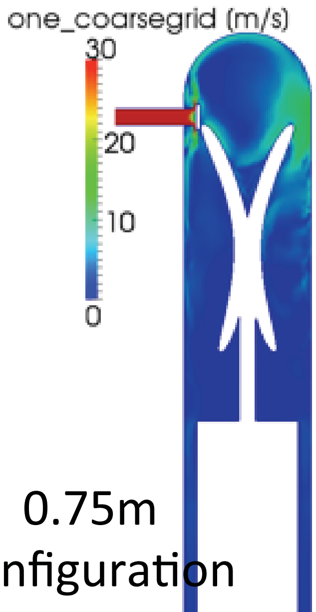
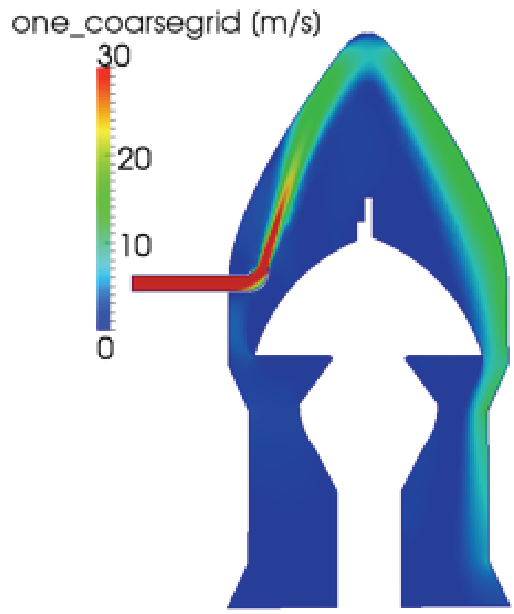
CFD Modeling

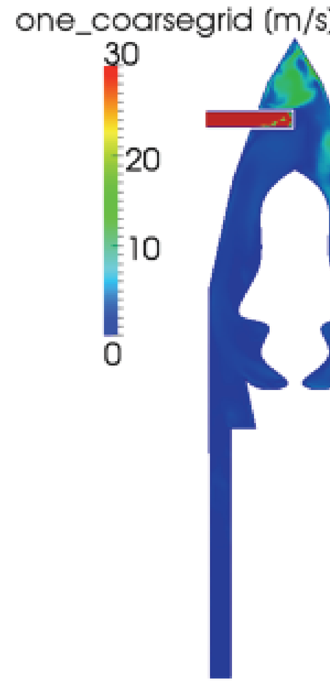
- OpenFoam - SimpleFoam



0.75m Configuration (6762865 number of cells)



3.5m Configuration (8594480 number of cells)



5.5m Configuration (6980673number of cells)

Chapter 5: Computational Fluid Dynamics Uncertainty Analysis

- Interpolation Scheme needed for CFD Uncertainty Analysis
- Feasibility of using Richardson's
  - Extrapolation for Entire Computational Domain
- Proposed CFD Uncertainty Method
  - Compared to Exact Solution – Laminar Flow Between Parallel Plates
- Proposed CFD Uncertainty Method Applied to
  - Heat Transfer over a Flat Plate

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Interpolation Method needed for Numerical Uncertainty Analysis of Computational Fluid Dynamics

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Summary of Richardson's Extrapolation

- Navier Stokes Equations
  - 2nd order, non-homogeneous, non-linear partial differential equations
- Richardson's Extrapolation is used to produce 4th order accurate solution from separate 2nd order accurate Navier Stokes Solutions

Summary of Richardson's Extrapolation

- ASME V&V 20-2009 Outlines a 5-step Procedure to Richardson's Extrapolation using Roache's (1998) Grid Convergence Index (GCI) Method
- Assumptions
  1. Three discrete solutions are in the asymptotic range
  2. Meshes have a uniform spacing over the domain
  3. Meshes are related through systematic refinement
  4. Solutions are smooth
  5. Other sources of numerical error are small

Solver Interpolation

- FLUENT
  - Includes a Mesh-to-Mesh Interpolation
  - Performs a zeroth-order (nearest neighbor) interpolation
  - Designed for initial conditions from a previous solution

- OPENFOAM
  - Mapfields fuction interpolation
  - Used for initialization of a solution from a previous model

- Using these ‘zeroth-order’ interpolation schemes is not sufficient for comparing errors from the mesh

Matlab Interpolation Schemes

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- Matlab
  - High level language used for numerical computations
- CFD data is in various forms
  - 1D, 2D, 3D, uniform, non-uniform
  - Generic Scheme is sought for all CFD data

	Matlab Function		
Interpolation Method	interp1	interp2	interp3
'nearest' - Nearest neighbor interpolation	X	X	X
'linear' - Linear interpolation (default)	X	X	X
'spline' - Cubic spline interpolation	X	X	X
'pchip' - Piecewise cubic Hermite interpolation	X		
'cubic'	X	X (uniformly-spaced only)	X (uniformly-spaced only)
'v5cubic' - cubic interpolation used in Matlab 5	X		

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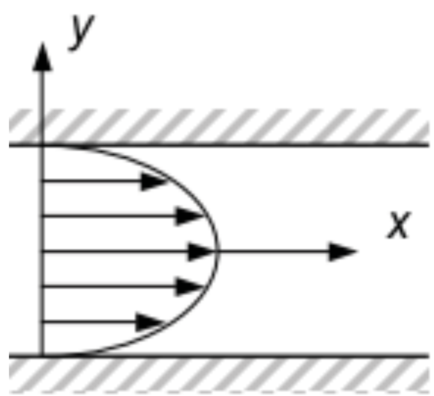
Example Problem

- Fully developed flow between parallel plates
  - Exact Solution to Navier Stokes
  - Provide a good example of errors that can be induced from interpolation

$$\bar{V} = -\frac{1}{12\mu}\left(\frac{\partial P}{\partial x}\right)a^2$$



$$u = \frac{a^2}{2\mu}\left(\frac{\partial P}{\partial x}\right)\left[\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right)\right]$$

a (m)	0.1
rho (kg/m3)	1.225
mu (Ns/m2)	0.00001789
dp/dx (N/m3)	-0.004

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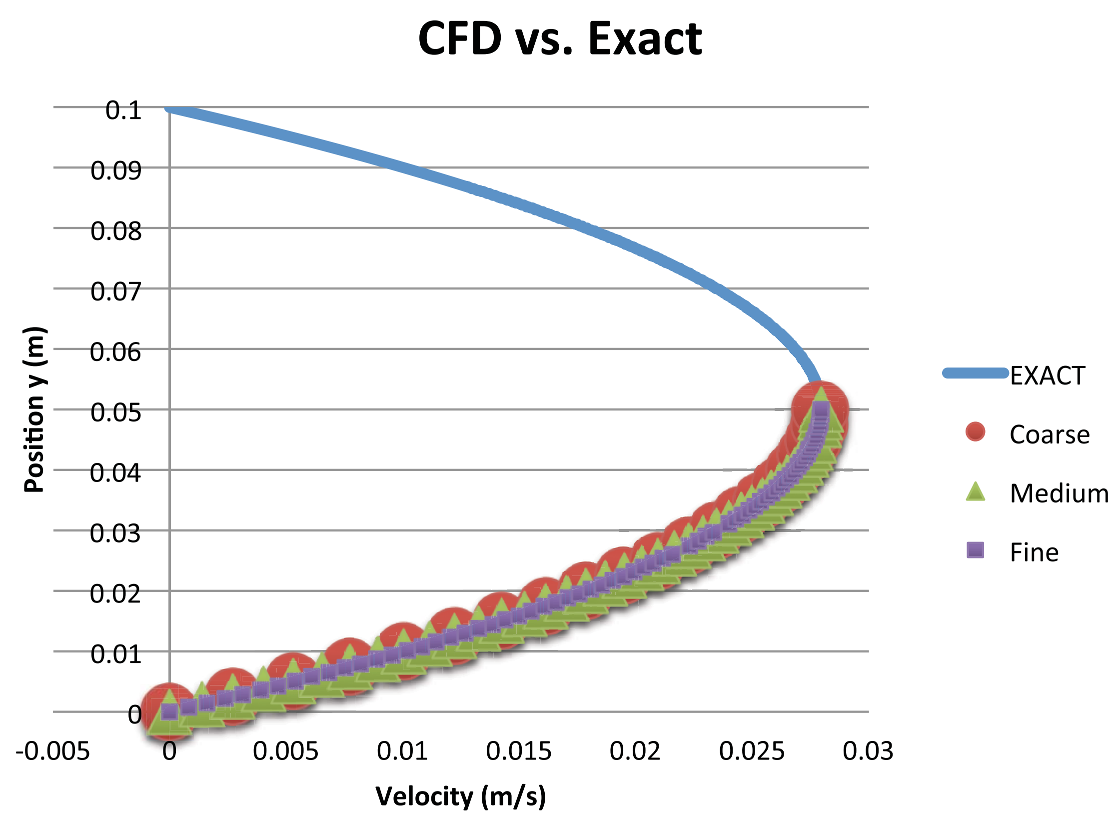
Example Problem

- Constructed a CFD Model in FLUENT
  - 3 Grids
    - Coarse, 7,140 Cells
    - Medium, 14,186 Cells
    - Fine, 24,780 Cells

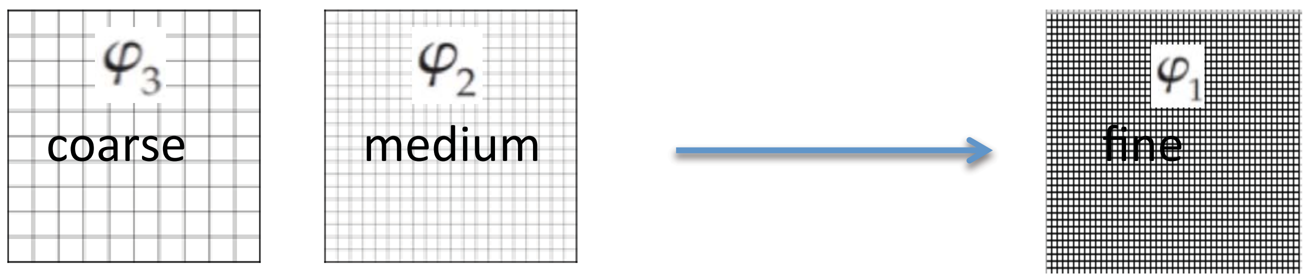


Example Problem

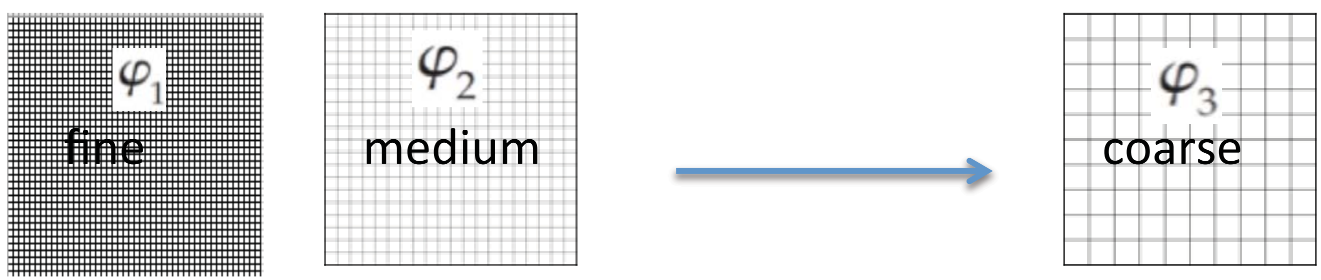
$$\varepsilon_{21} = \varphi_2 - \varphi_1$$
$$\varepsilon_{32} = \varphi_3 - \varphi_2$$

- Interpolation Direction?

1. Interpolate Coarse and Medium Mesh -> Fine

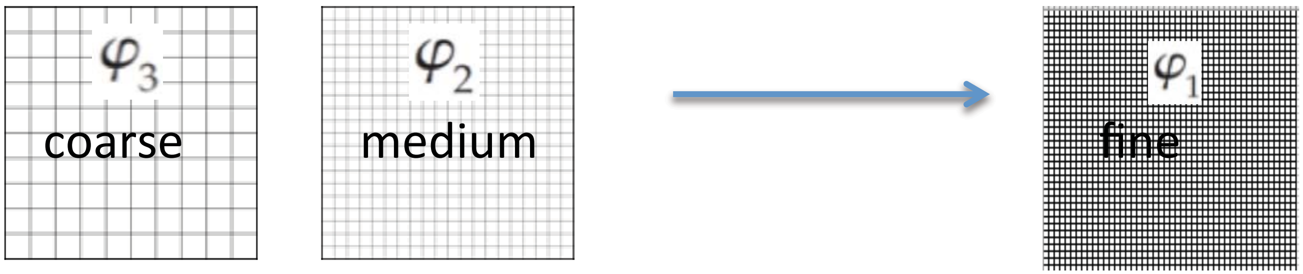


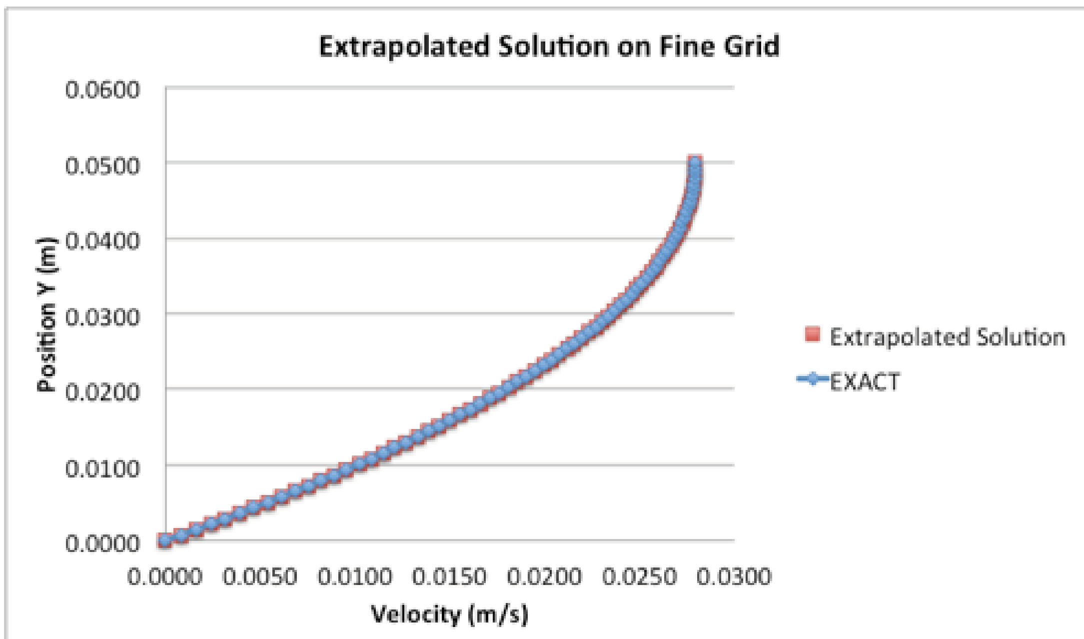
2. Interpolate Medium and Fine Mesh -> Coarse



Example Problem

1. Linearly Interpolate Coarse and Medium Mesh -> Fine

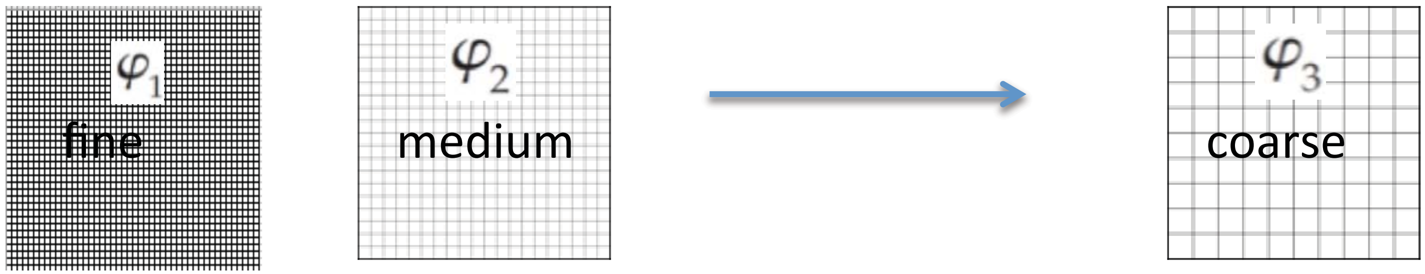


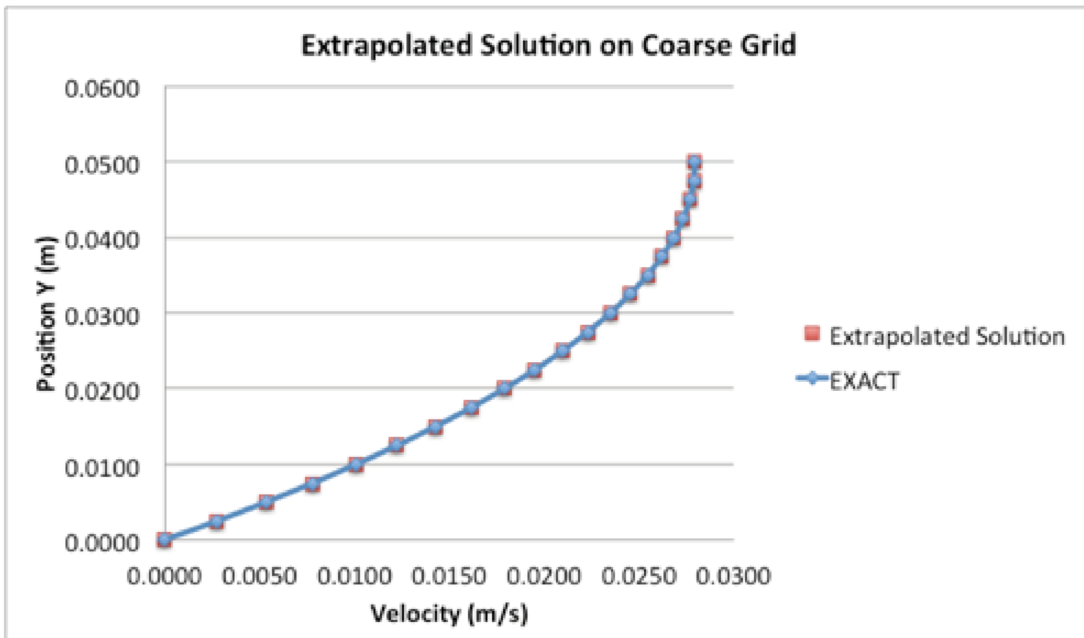


Max % Error Extrapolated Values	Average % Error Extrapolated Values
0.8950	0.0596

Example Problem

2. Linearly Interpolate Fine and Medium Mesh -> Coarse



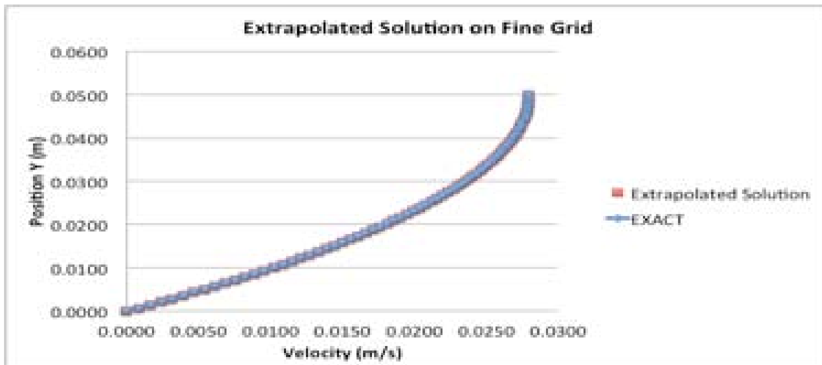


Max % Error Extrapolated Values	Average % Error Extrapolated Values
0.0792	0.0175

Example Problem

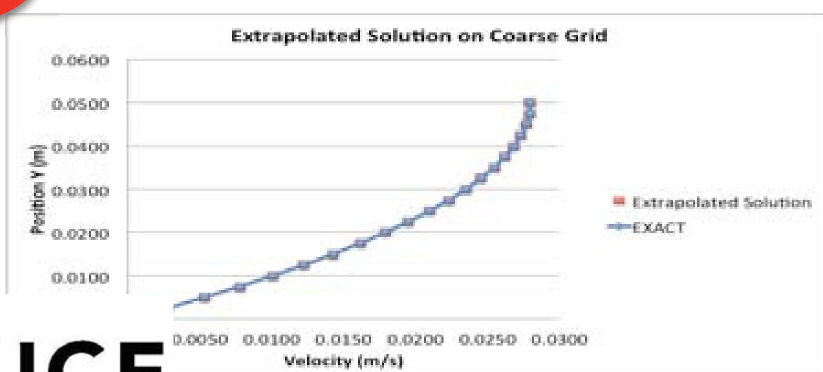
- Interpolation Direction?

1. Interpolate Coarse and Medium Mesh -> Fine



Max % Error Extrapolated Values	Average % Error Extrapolated Values
0.8950	0.0596

2. Interpolate Medium and Fine Mesh -> Coarse



Max % Error Extrapolated Values	Average % Error Extrapolated Values
0.0792	0.0175

Example Problem

Grids	Max % Error	Average % Error
(Coarse vs Exact)	0.1910	0.1265
(Medium vs Exact)	0.0969	0.0367
(Fine vs Exact)	0.0289	0.0121

1. Linearly Interpolated Coarse, Medium to Fine		
(Interpolated Coarse vs Exact)	1.9760	0.2528
(Interpolated Medium vs Exact)	0.6322	0.0679

2. Linearly Interpolated Medium, Fine to Coarse		
(Interpolated Medium vs Exact)	0.0728	0.0362
(Interpolated Fine vs Exact)	0.0787	0.0223

Extrapolated		
1. Linear Interpolation Coarse and Medium to Fine (Extrapolated vs Exact)	0.8950	0.0596
2. Linear Interpolation Medium and Fine to Coarse (Extrapolated vs Exact)	0.0792	0.0175

Example Problem

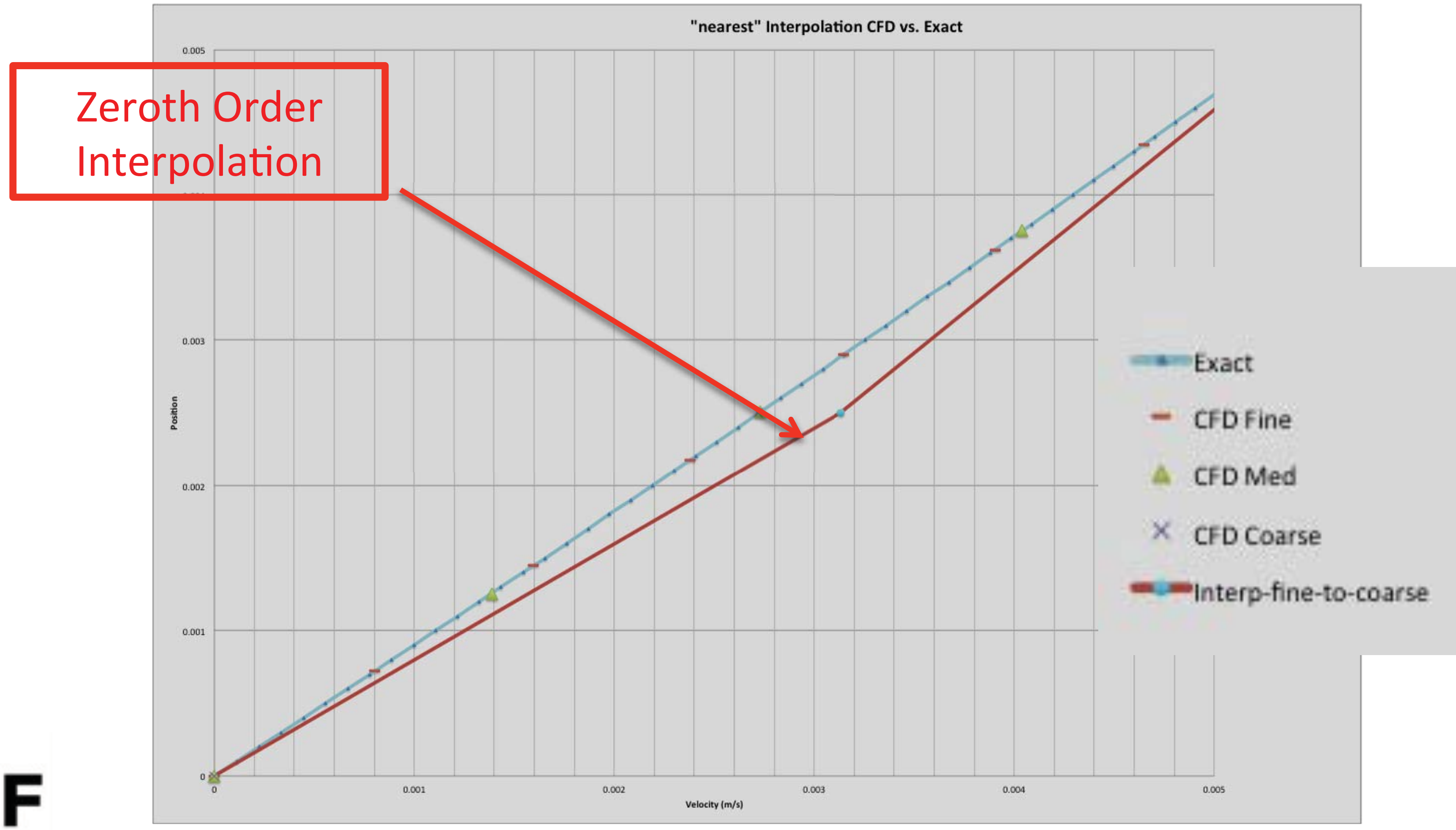
- Interpolating to the coarse grid was selected
- Other interpolation methods
  - "nearest" – Fluent's Mesh-to-Mesh
  - "linear" – Matlab

    yfi = interp1(fine(:,2),fine(:,1),coarse(:,2),'linear')
  - "cubic" – Matlab

    yfi = interp1(fine(:,2),fine(:,1),coarse(:,2),'cubic')

Example Problem

- “nearest” – Fluent’s Mesh-to-Mesh

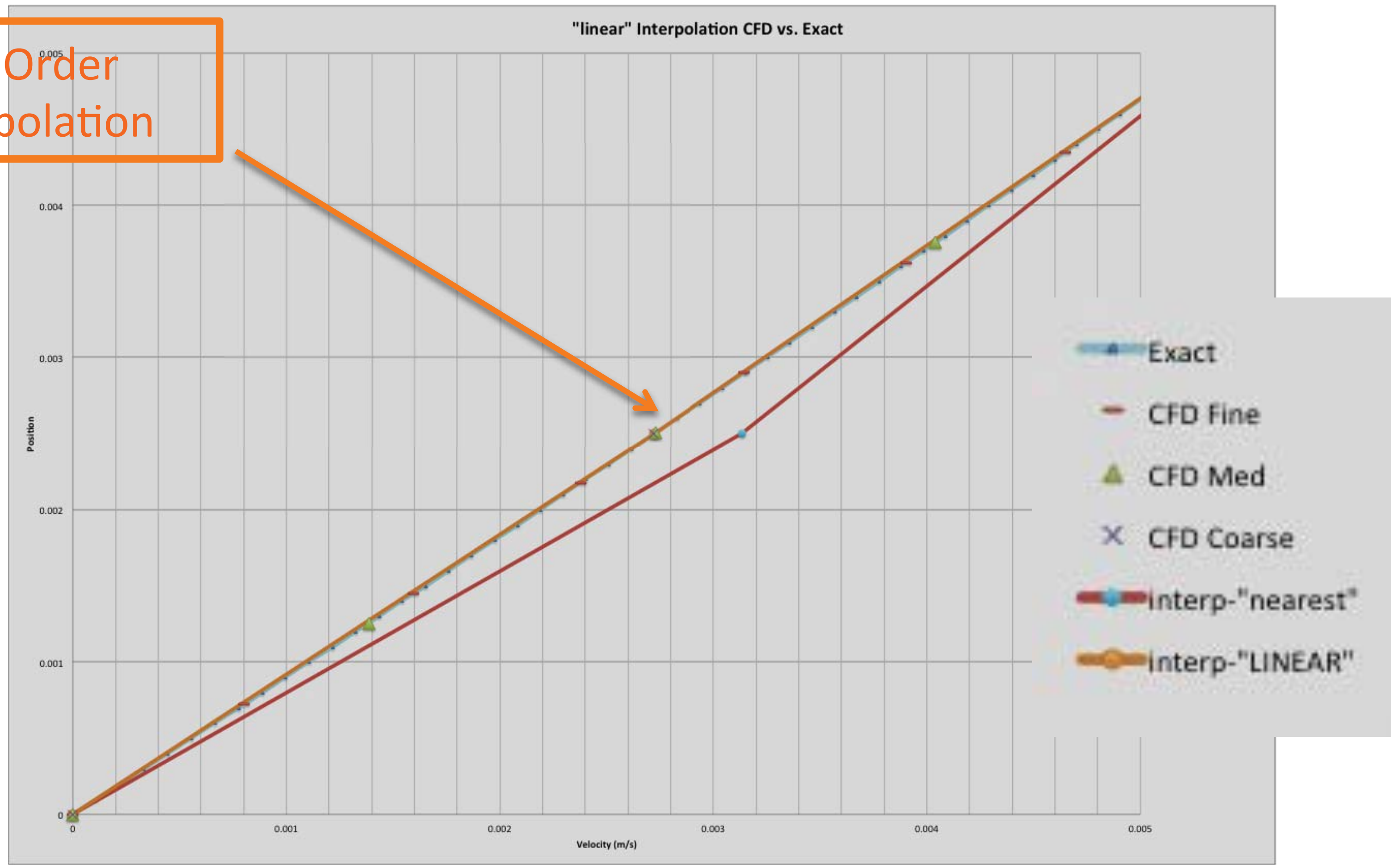


Example Problem

- “linear” – Matlab

yfi = interp1(fine(:,2),fine(:,1),coarse(:,2),'linear')

1st Order Interpolation

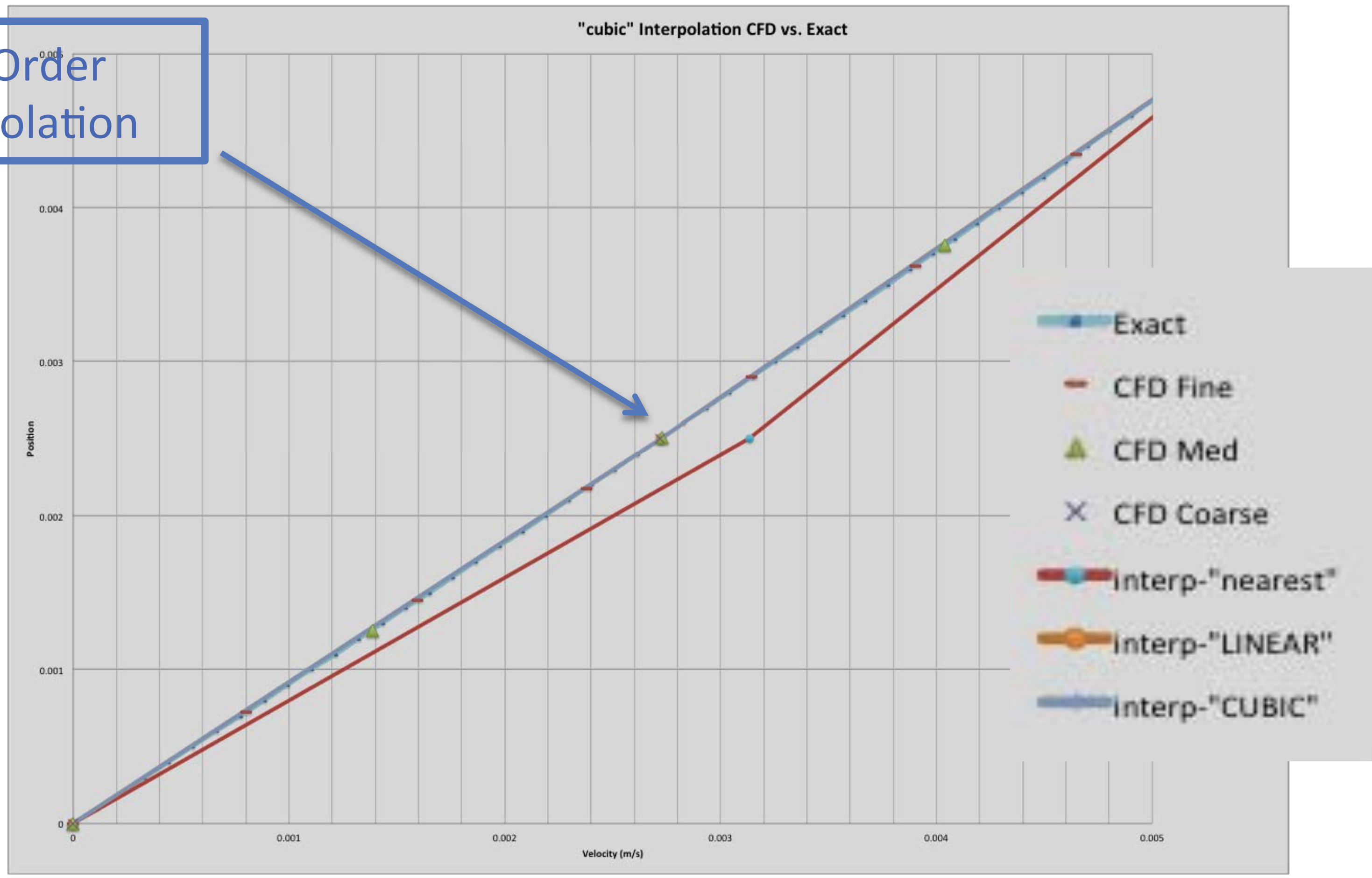


Example Problem

- "cubic" – Matlab

yfi = interp1(fine(:,2),fine(:,1),coarse(:,2),'cubic')

3rd Order Interpolation



Matlab Interpolation Schemes

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- Extending the Interpolation Schemes to 2D and 3D
  - Interp2 and Interp3 Matlab Functions
    - Require use of MeshGrid
      - Transforms the domain of vectors into arrays
      - For Meshes in the 4 million to 8 million Cell Range
        - Error “Maximum variable size allowed by program is exceeded”
  - Griddata Function
    - Nearest, Linear, Natural, Cubic, and v4
    - Nearest, Linear, and Natural are the only options available in 2D and 3D
- The only options available for 1D, 2D, and 3D
  - Interp1 and Griddata – ‘nearest’ and ‘linear’

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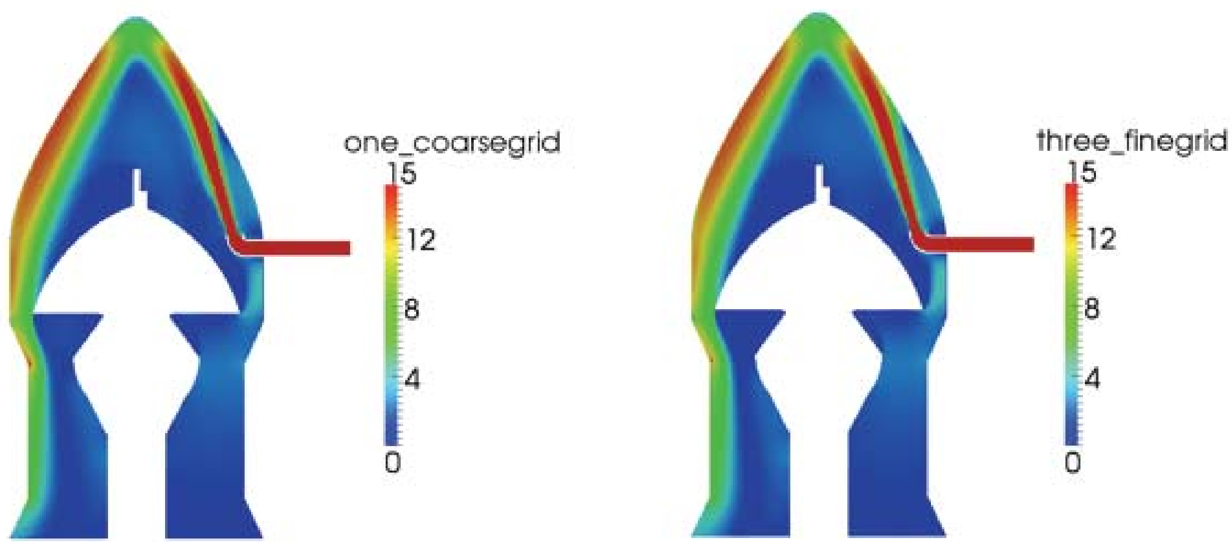
3D Example

- Airflow around encapsulated spacecraft
  - Matlab griddata ‘linear’ option used
  - Interpolating Fine and Medium Grid onto Coarse Grid



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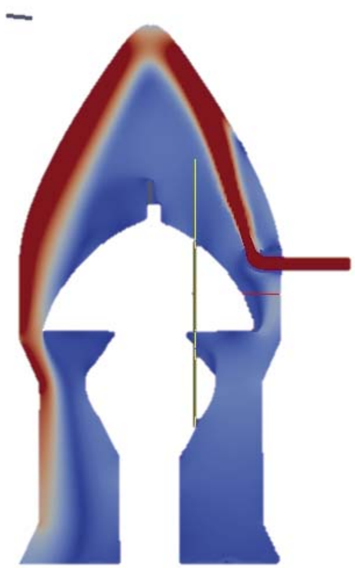
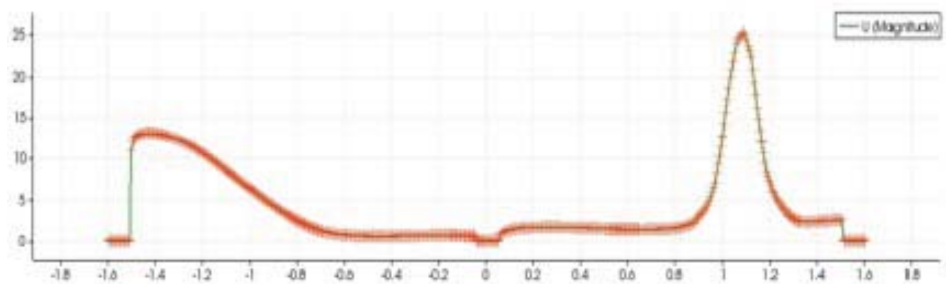
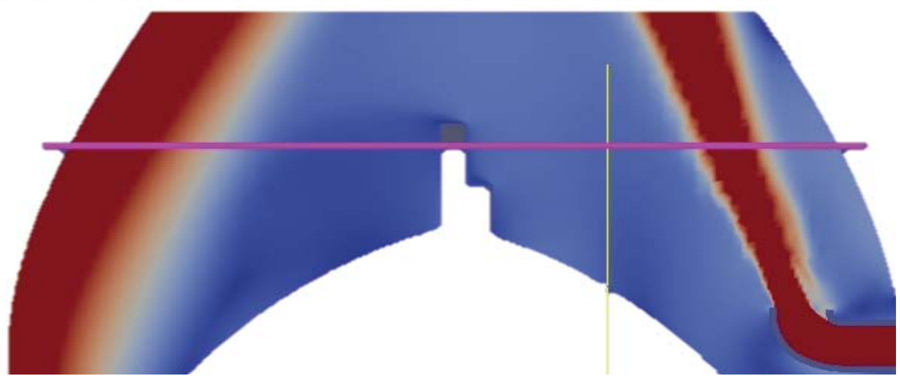
3D Example

- Comparing using a Line Plot

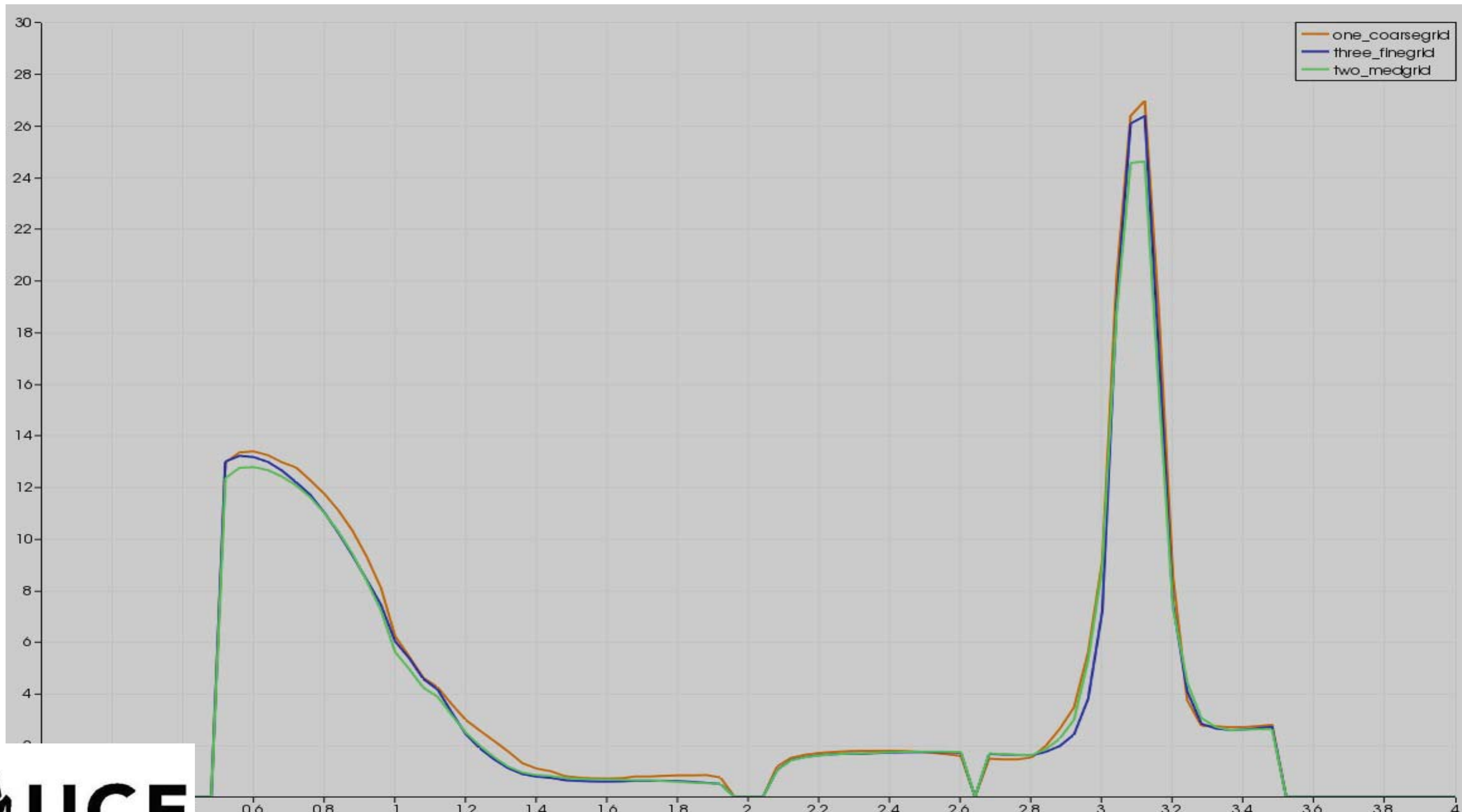






3D Example

- Comparing using a Line Plot



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AIAA-2014-1433 Conclusion / Recommendation

- By comparing the interpolation schemes in one, two, and three dimensions and investigating the options that are readily available in Matlab
  - Recommend the "linear" option be used when comparing the error or uncertainty due to the grid
    - interp1 or griddata Matlab commands
- If coarse grid has the level of detail required
  - Recommend interpolating from the fine and medium grids onto the coarse grid
    - Lower Error in the Extrapolated Solution
    - Smaller Data Set

– Future Work include higher order interpolation schemes in 3D (Radial Basis Function Interpolation, 4^{th} order)

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Feasibility of using Richardson's Extrapolation for Entire Computational Domain

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Summary of Method

- Following method outlined by Stern, Wilson, Coleman, and Paterson
- Convergence studies require a minimum of three solutions to evaluate convergence with respect to an input parameter. Consider the situation for 3 solutions corresponding to fine S_{k1}, medium S_{k2}, and coarse S_{k3} values for the *kth* input parameter. Solution changes **ε** for medium-fine and coarse-medium solutions and their ratio R_k are defined by:

$$\boldsymbol{\varepsilon_{21} = S_{k2} - S_{k1}}$$
$$\boldsymbol{\varepsilon_{32} = S_{k3} - S_{k2}}$$
$$\boldsymbol{R_k = \varepsilon_{21} / \varepsilon_{32}}$$

- Three convergence conditions are possible:

Monotonic convergence: $0 < R_k < 1$

Oscillatory convergence: $R_k < 0^i$

Divergence: $R_k > 1$

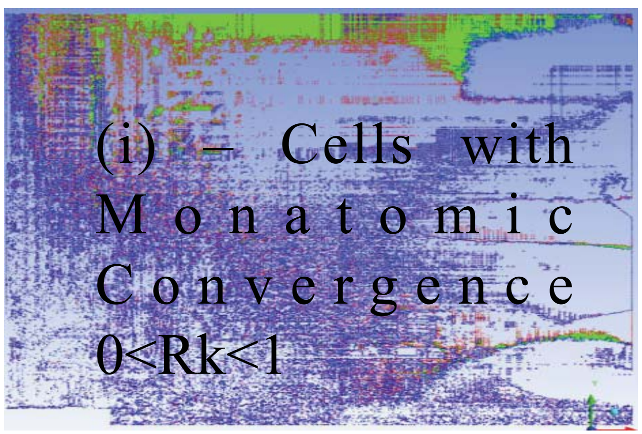
Results (Monotonic Convergence?) Backward Facing Step

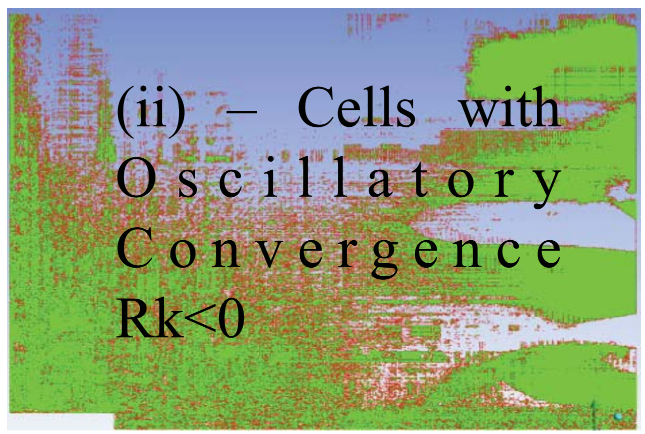
Three convergence conditions are possible:

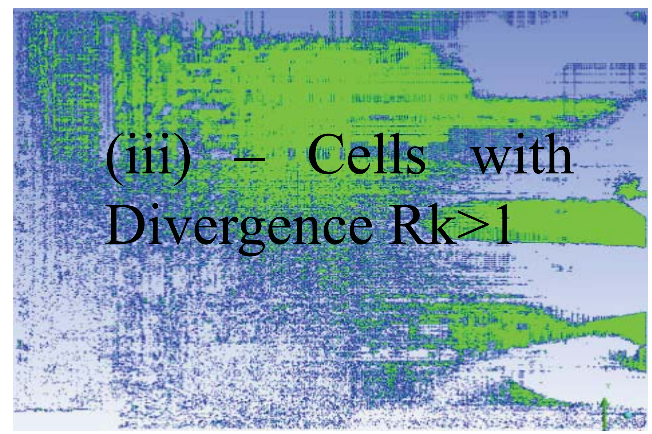
Monotonic convergence: $0 < R_k < 1$

Oscillatory convergence: $R_k < 0$[i]

Divergence: $R_k > 1$







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Results (Monotonic Convergence?) Spacecraft / ECS System

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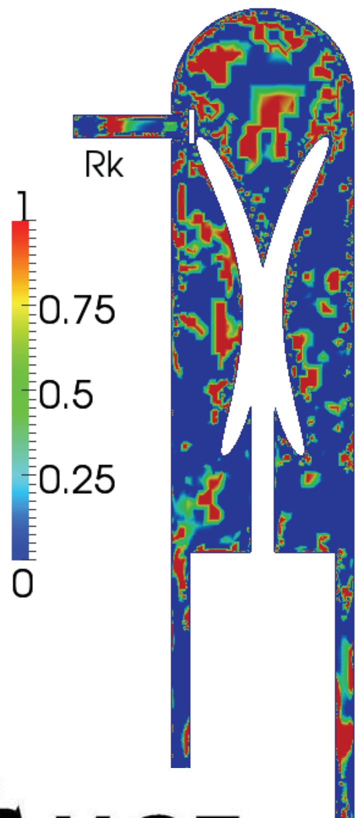
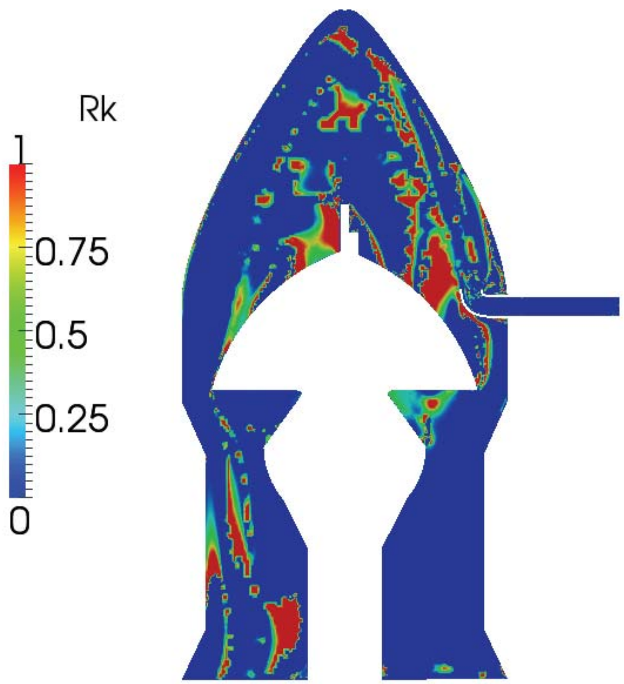
Three convergence conditions are possible:

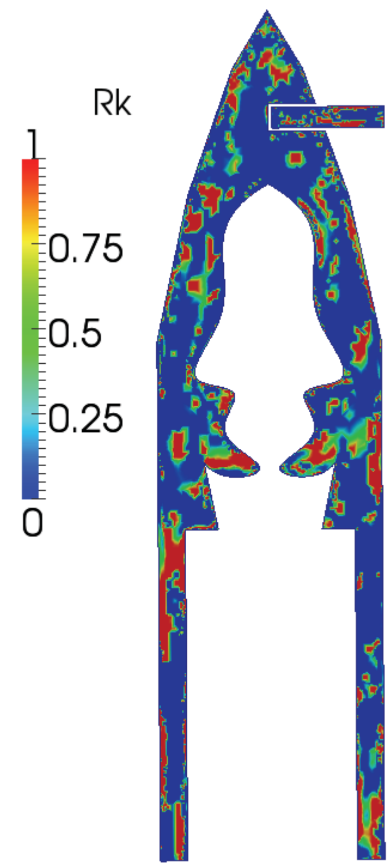
Monotonic convergence: $0 < R_k < 1$

Oscillatory convergence: $R_k < 0$[i]

Divergence: $R_k > 1$







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Proposed CFD Uncertainty Method Compared to Exact Solution – Laminar Flow Between Parallel Plates

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Example Fully Developed Laminar Flow between Parallel Plates

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- Heat Transfer Correlations, Traditional
- The uncertainty analysis will follow the methodology laid out by Coleman and Steele (Experimentation and Uncertainty Analysis for Engineers, 2nd ed, J. Wiley and Sons, 1999). This methodology is in line with the ISO Guide to the Expression of Uncertainty in Measurement (1993).

$$U = \left(\underbrace{\sum_{i=1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)^2 B_i^2\right\}}_{\text{Bias}} + \underbrace{2\sum_{i=1}^{J}\sum_{k=i+1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)\left(\frac{\partial r}{\partial X_k}\right)[B_i B_k]_{correlated}\right\}}_{\text{Correlated}} + \underbrace{\sum_{i=1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)^2 P_i^2\right\}}_{\text{Random}}\right)^{1/2}$$

$$\boxed{u = \frac{a^2}{2\mu}\left(\frac{\eth P}{\eth x}\right)\left[\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right)\right]}$$

$$\frac{\partial u}{\partial \mu} = -\frac{\eth P}{\eth x} * y * (y-a)/(2\mu)$$

$$\frac{\partial u}{\partial \frac{\eth P}{\eth x}} = \frac{a^2}{2\mu}\left[\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right)\right]$$

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Example Fully Developed Laminar Flow between Parallel Plates

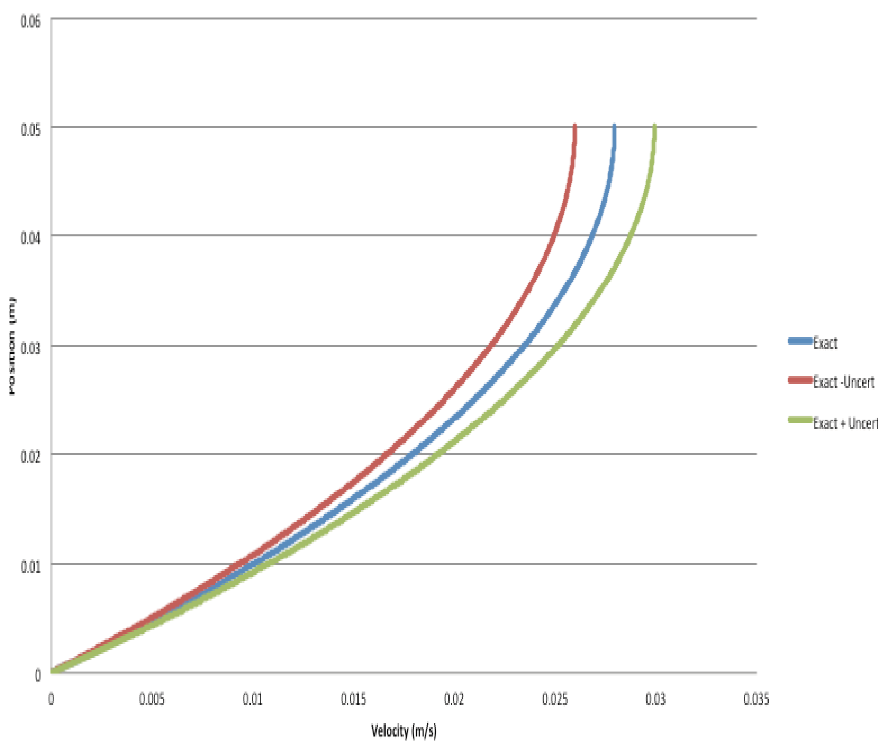
- Uncertainty for 5% Bias in pressure gradient and viscosity

$$u_u = \left(\left(\left(-\frac{\eth P}{\eth x} * y * (y-a)/(2\mu) \right)^2 B_\mu^2 \right) + \left(\left(\frac{a^2}{2\mu} \left[\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right) \right] \right)^2 B_{\frac{\eth P}{\eth x}}^2 \right) \right)^{1/2}$$

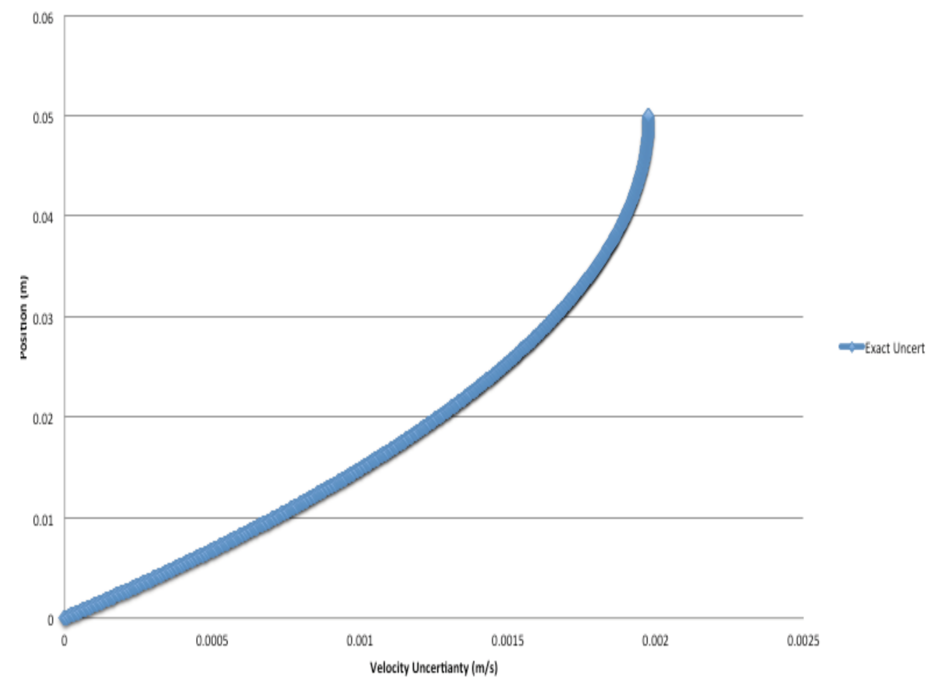
Example Fully Developed Laminar Flow between Parallel Plates

- Numerically Evaluating (Traditional):

Exact Solution with Uncertainty



Uncertainty



Proposed Methodology using CFD Only

CFD Uncertainty Cases

1	Coarse Grid
2	Medium Grid
3	Fine Grid
4	Velocity Low
5	Velocity High
6	Density Low
7	Density High
8	Outlet Pressure Low
9	Outlet Pressure High
10	Solver

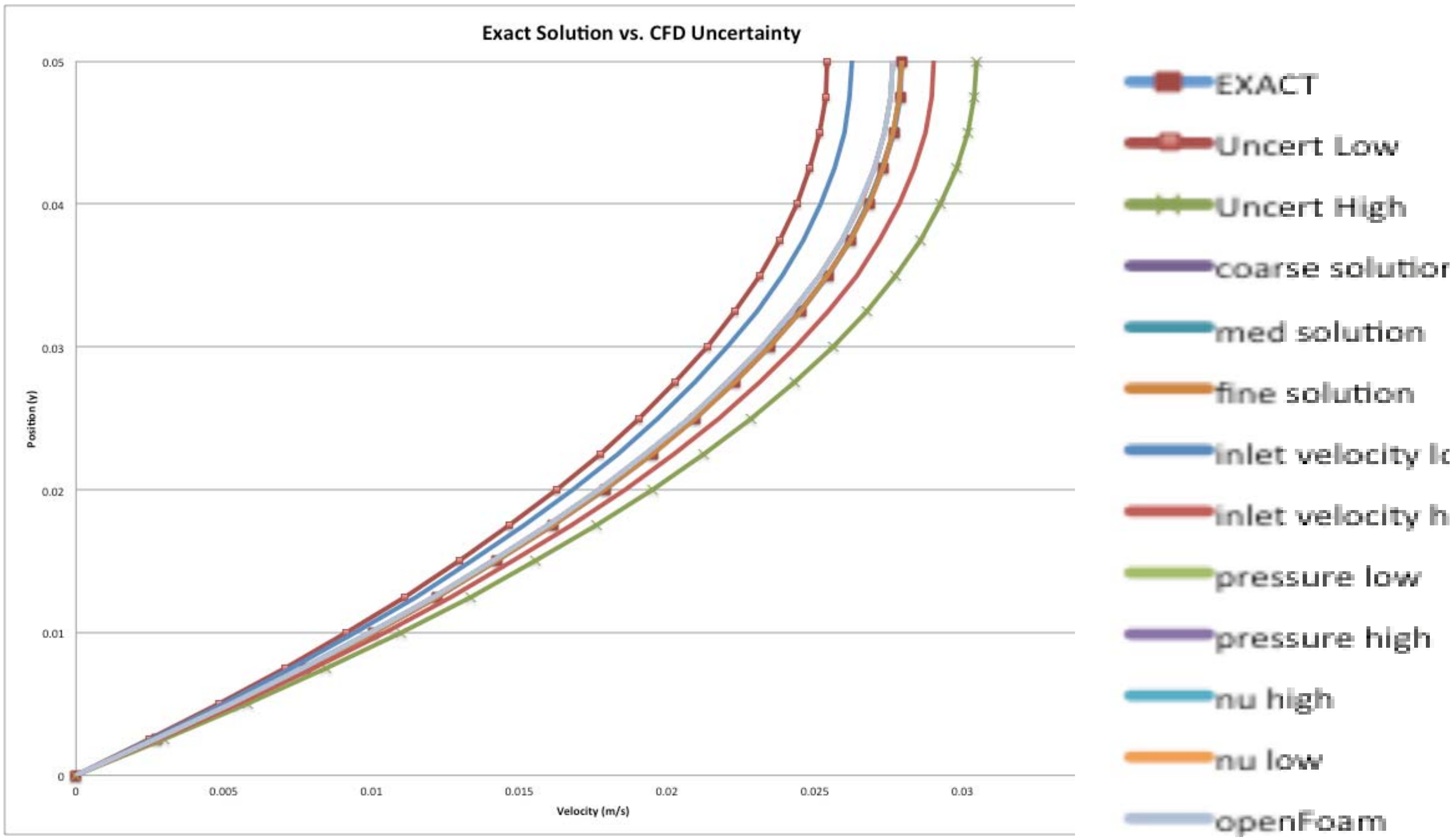
Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
[illegible]	[illegible]	[illegible]
10	9	1.833
12	11	1.796
13	12	1.782
14	13	1.771

$$u_{val} = 1.833 * \left(\left(\left(\frac{\partial V}{\partial num}\right)^2 B_{num}^2\right) + \left(\left(\frac{\partial V}{\partial velocity}\right)^2 B_{velocity}^2\right) + \left(\left(\frac{\partial V}{\partial pressure}\right)^2 B_{pressure}^2\right) + + \left(\left(\frac{\partial V}{\partial rho}\right)^2 B_{rho}^2\right) + \left(\frac{\partial V}{\partial solver}\right)^2 B_{solver}^2 \right)^{1/2}$$

$$\boxed{u_{val} = 1.833 * \left|\frac{1}{2}(S_U - S_L)\right|}$$

Proposed Methodology using CFD Only

- Results for proposed methodology



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Comparison of Methods

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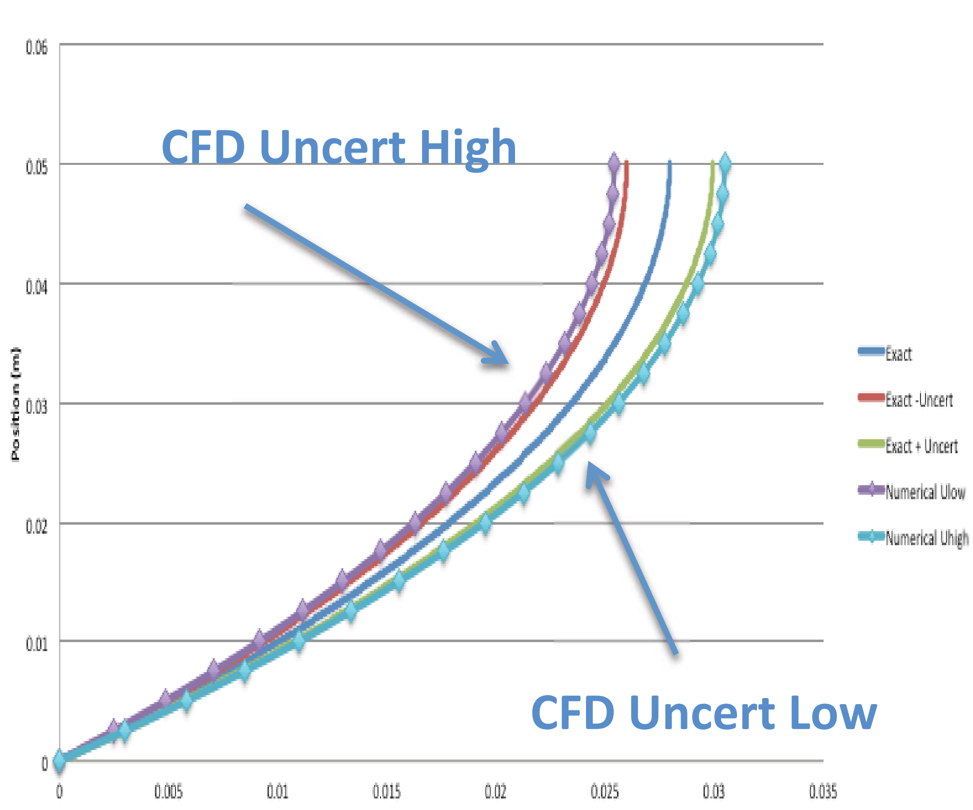
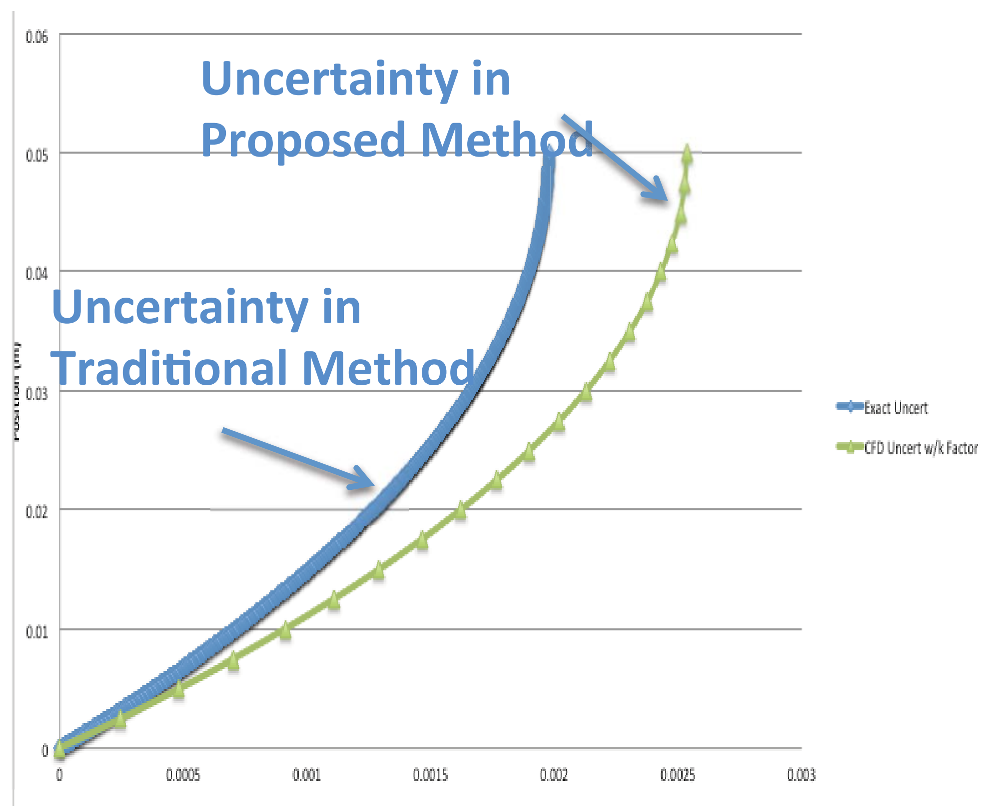
- Traditional vs. Proposed

Velocity



Uncertainty



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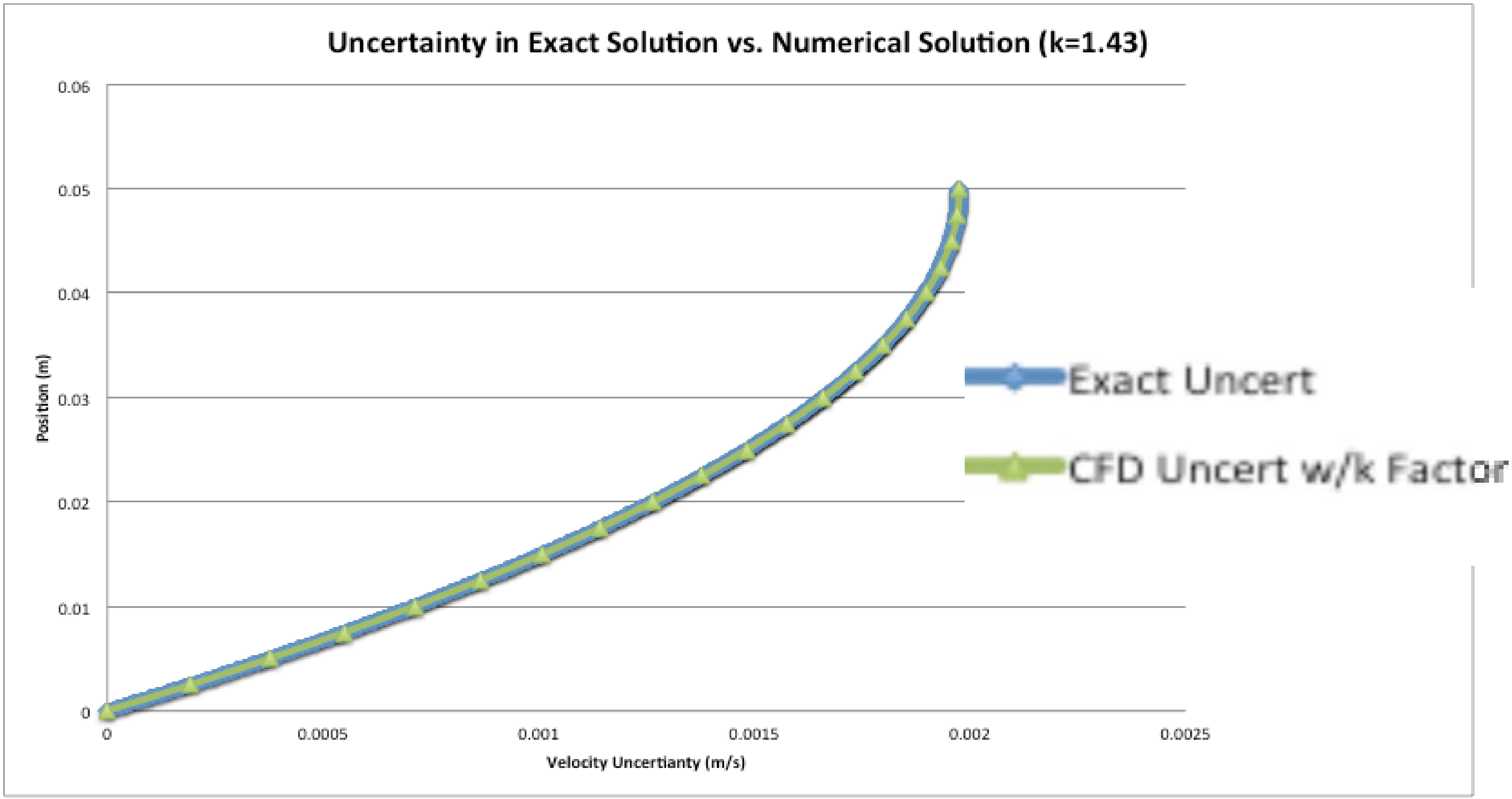
Comparison of Methods

- Traditional vs. Proposed



Conclusion Example Fully Developed Laminar Flow between Parallel Plates

- Proposed Method Envelops the True value and uses only CFD Data to Estimate the Uncertainty for Laminar Flow between Parallel Plates
  - No Testing

- Proposed methodology can be used to conservatively estimate the uncertainty in CFD models

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Computational Fluid Dynamics Uncertainty Analysis applied to Heat Transfer over a Flat Plate

APS-DFD13-2013-000087

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Example Heat Transfer over Flat Plate

- Heat Transfer Correlations, Traditional
- The uncertainty analysis will follow the methodology laid out by Coleman and Steele (Experimentation and Uncertainty Analysis for Engineers, 2nd ed, J. Wiley and Sons, 1999). This methodology is in line with the ISO Guide to the Expression of Uncertainty in Measurement (1993).

$$U = \left(\underbrace{\sum_{i=1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)^2 B_i^2\right\}}_{\text{Bias}} + \underbrace{2\sum_{i=1}^{J}\sum_{k=i+1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)\left(\frac{\partial r}{\partial X_k}\right)[B_i B_k]_{correlated}\right\}}_{\text{Correlated}} + \underbrace{\sum_{i=1}^{J}\left\{\left(\frac{\partial r}{\partial X_i}\right)^2 P_i^2\right\}}_{\text{Random}}\right)^{1/2}$$

$$\boxed{h = c\left(\frac{\rho V L}{\mu}\right)^{4/5}\frac{k}{L}}$$

$$\frac{dh}{dV} = \frac{4ck\rho}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}} \qquad \frac{dh}{d\mu} = -\frac{4CVk\rho}{5\mu^2\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}$$

$$\frac{dh}{d\rho} = \frac{4ckV}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}} \qquad \frac{dh}{dL} = \frac{4CVk\rho}{5L\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}} - \frac{Ck\left(\frac{LV\rho}{\mu}\right)^{4/5}}{L^2}$$

$$\frac{dh}{dk} = \frac{c}{L}\left(\frac{LV\rho}{\mu}\right)^{4/5} \qquad \frac{dh}{dC} = \frac{k}{L}\left(\frac{\rho V L}{\mu}\right)^{4/5}$$

Example Heat Transfer over Flat Plate

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- Heat Transfer Correlation Uncertainty

$$U_h = \left(\left(\left(\frac{\partial h}{\partial V}\right)^2 B_V^2\right) + \left(\left(\frac{\partial h}{\partial \rho}\right)^2 B_\rho^2\right) + \left(\left(\frac{\partial h}{\partial k}\right)^2 B_k^2\right) + \left(\left(\frac{\partial h}{\partial \mu}\right)^2 B_\mu^2\right) + \left(\left(\frac{\partial h}{\partial L}\right)^2 B_L^2\right) + \left(\left(\frac{\partial h}{\partial C}\right)^2 P_C^2\right) + 2\left(\frac{\partial h}{\partial \rho}\right)\left(\frac{\partial h}{\partial k}\right) B_\rho B_k + 2\left(\frac{\partial h}{\partial \rho}\right)\left(\frac{\partial h}{\partial \mu}\right) B_\rho B_\mu + 2\left(\frac{\partial h}{\partial k}\right)\left(\frac{\partial h}{\partial \mu}\right) B_k B_\mu\right)^{1/2}$$

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Example Heat Transfer over Flat Plate

- Plug in Partial Derivatives

c	
Seban & Doughty	0.0236
Jakob	0.024
Sugawara	0.023
Fundamentals of Heat and Mass Transfer	0.0296
c middle	0.0263
c uncert (random)	0.0033

Variable	Bias
Velocity, V	3%
Density, rho	3%
Thermal Conductivity, k	3%
Viscosity, mu	3%

$$
\begin{aligned}
U_h = \Bigg(& \left(\left(\frac{4ck\rho}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right)^2 B_V^2\right) + \left(\left(\frac{4ckV}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right)^2 B_\rho^2\right) + \left(\left(\frac{c}{L}\left(\frac{LV\rho}{\mu}\right)^{4/5}\right)^2 B_k^2\right) + \\
& \left(\left(\frac{\partial h}{\partial \mu}\right)^2 B_\mu^2\right) + \left(\left(\frac{4CVk\rho}{5L\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}} - \frac{Ck\left(\frac{LV\rho}{\mu}\right)^{4/5}}{L^2}\right)^2 B_L^2\right) + \left(\left(\frac{k}{L}\left(\frac{\rho VL}{\mu}\right)^{4/5}\right)^2 P_C^2\right) + \\
& 2\left(\frac{4ckV}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right)\left(\frac{c}{L}\left(\frac{LV\rho}{\mu}\right)^{4/5}\right) B_\rho B_k + 2\left(\frac{4ckV}{5\mu\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right)\left(-\frac{4CVk\rho}{5\mu^2\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right) B_\rho B_\mu + \\
& 2\left(\frac{c}{L}\left(\frac{LV\rho}{\mu}\right)^{4/5}\right)\left(-\frac{4CVk\rho}{5\mu^2\left(\frac{LV\rho}{\mu}\right)^{\frac{1}{5}}}\right) B_k B_\mu \Bigg)^{1/2}
\end{aligned}
$$

Example Heat Transfer over Flat Plate

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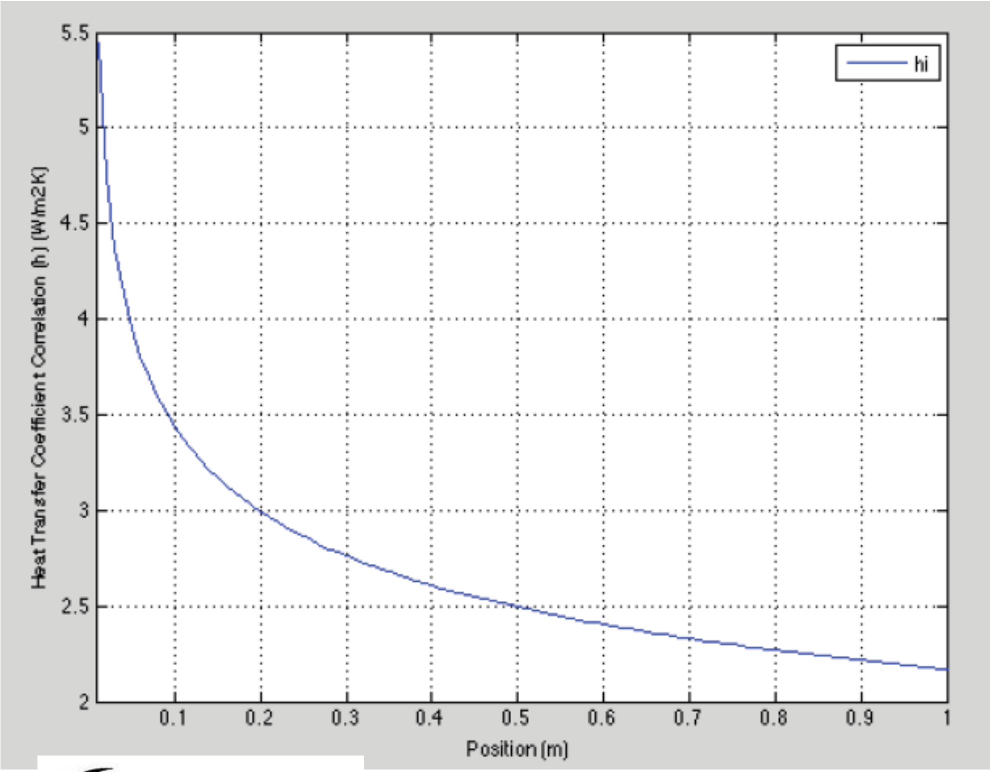
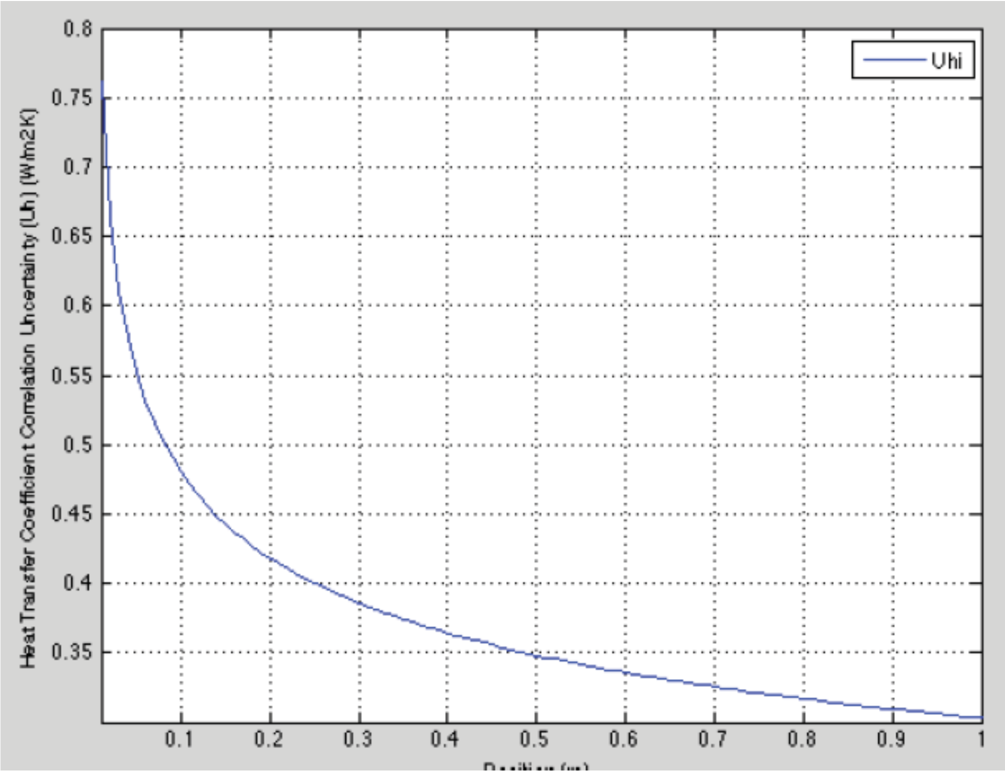
- Numerically Evaluating (Traditional):

Heat Transfer Coefficient



Uncertainty in Heat Transfer Coefficient



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Proposed Methodology using CFD Only

	CFD Uncertainty Cases
1	Coarse Grid
2	Medium Grid
3	Fine Grid
4	Velocity Low
5	Velocity High
6	Density Low
7	Density High
8	Thermal Conductivity High
9	Thermal Conductivity Low
10	Viscosity Low
11	Viscosity High
12	SA Turbulence Model
13	kwSST Turbulence Model

Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
9	8	1.86
10	9	1.833
11	10	1.812
12	11	1.796
13	12	1.782

$$U_h = \left(\left(\left(\frac{\partial h}{\partial V}\right)^2 B_V^2 \right) + \left(\left(\frac{\partial h}{\partial \rho}\right)^2 B_\rho^2 \right) + \left(\left(\frac{\partial h}{\partial k}\right)^2 B_k^2 \right) + \left(\left(\frac{\partial h}{\partial \mu}\right)^2 B_\mu^2 \right) + \left(\left(\frac{\partial h}{\partial L}\right)^2 B_L^2 \right) + \right.$$

$$\left(\left(\frac{\partial h}{\partial C}\right)^2 P_C^2 \right) + 2\left(\frac{\partial h}{\partial \rho}\right)\left(\frac{\partial h}{\partial k}\right) B_\rho B_k + 2\left(\frac{\partial h}{\partial \rho}\right)\left(\frac{\partial h}{\partial \mu}\right) B_\rho B_\mu +$$

$$\left. 2\left(\frac{\partial h}{\partial k}\right)\left(\frac{\partial h}{\partial \mu}\right) B_k B_\mu \right)^{1/2}$$

$$\boxed{u_{val} = 1.782 * \left|\frac{1}{2}(S_U - S_L)\right|}$$

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Proposed Methodology using CFD Only

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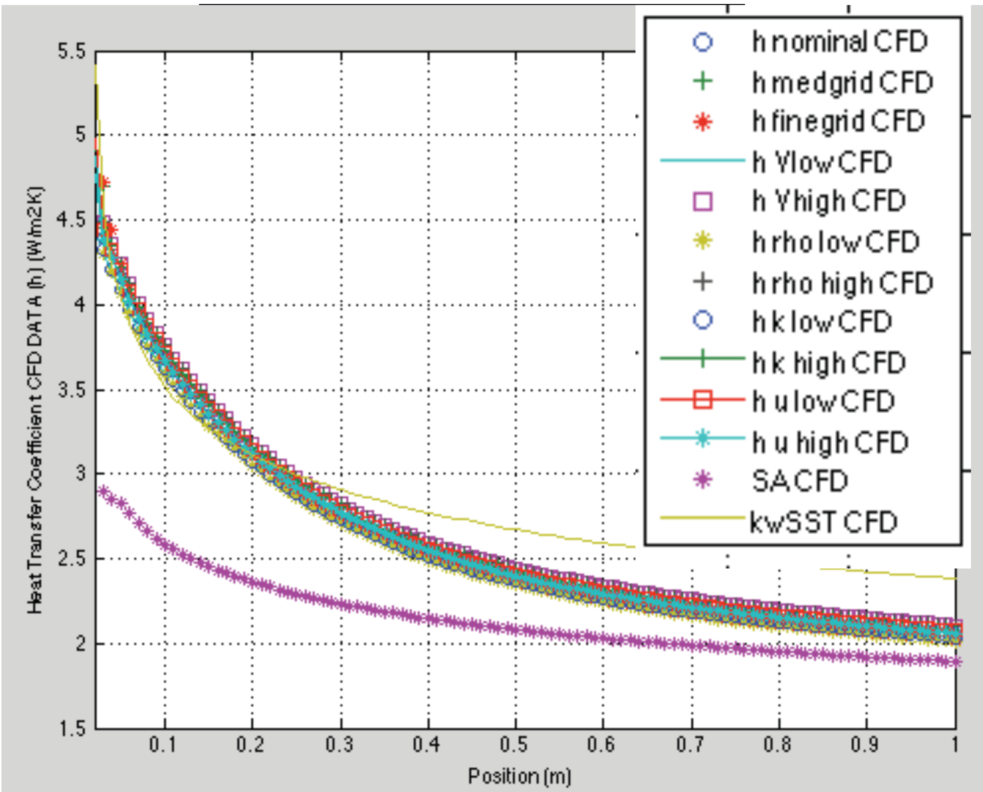
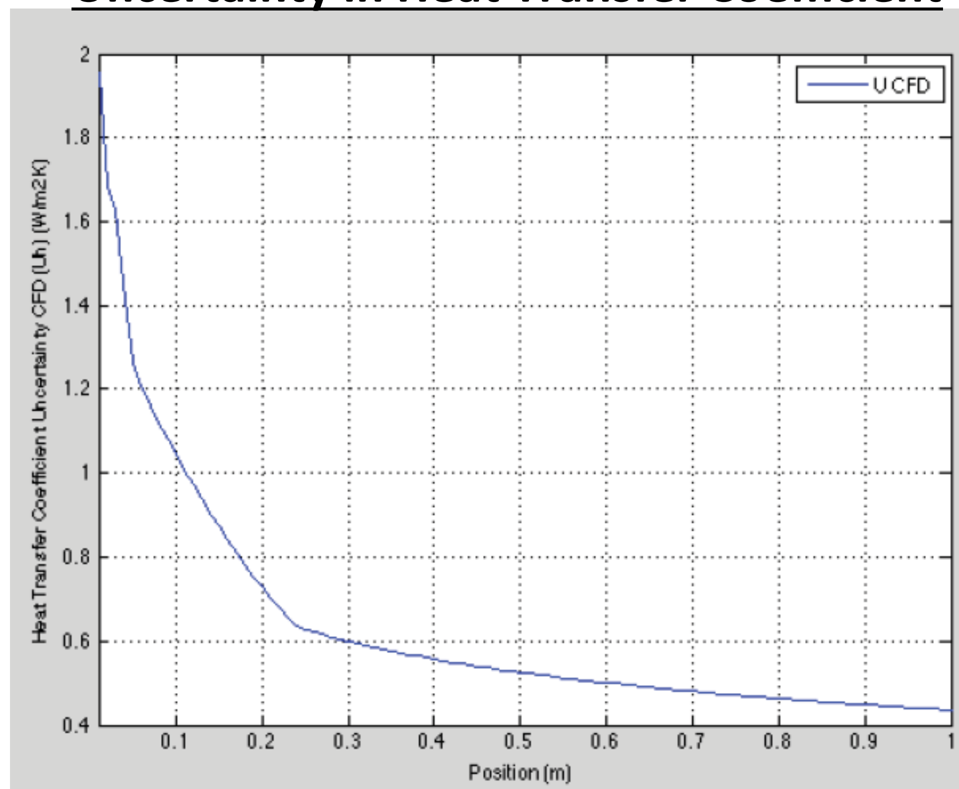
- Results for proposed methodology

Heat Transfer Coefficient



Uncertainty in Heat Transfer Coefficient



	Average Difference in htc (W/m2K)	Ranking
Turbulence	0.693102673	1
Grid	0.130514851	2
Velocity	0.117431782	3
Density	0.117431683	4
k (thermal conductivity)	0.069466139	5
Viscosity	0.021837228	6

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Comparison of Methods

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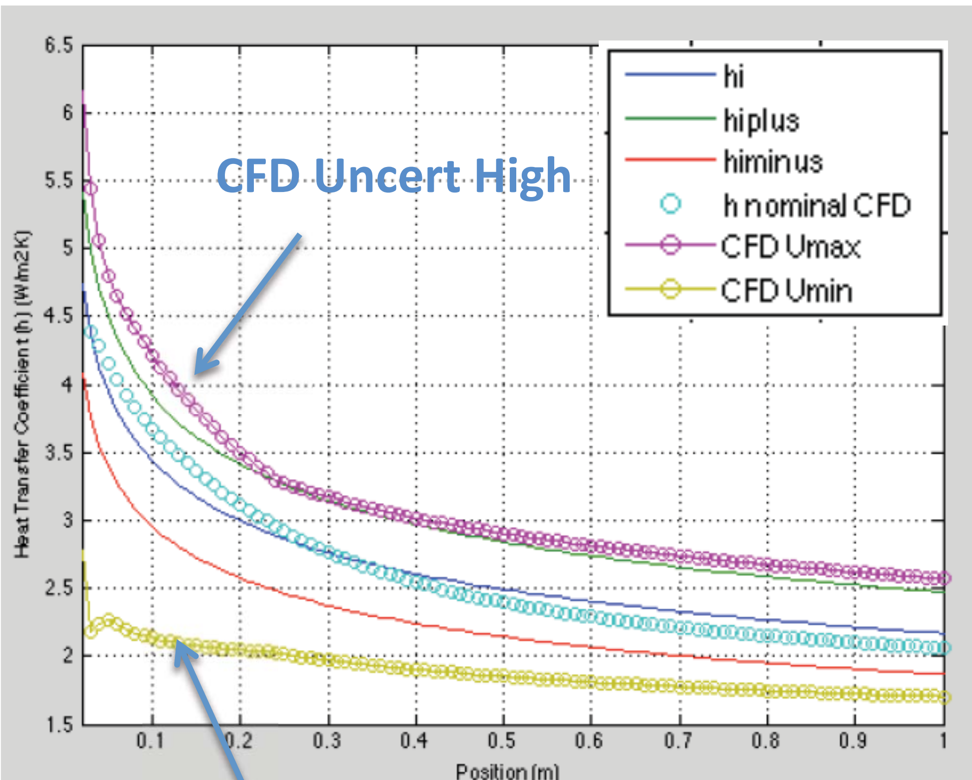
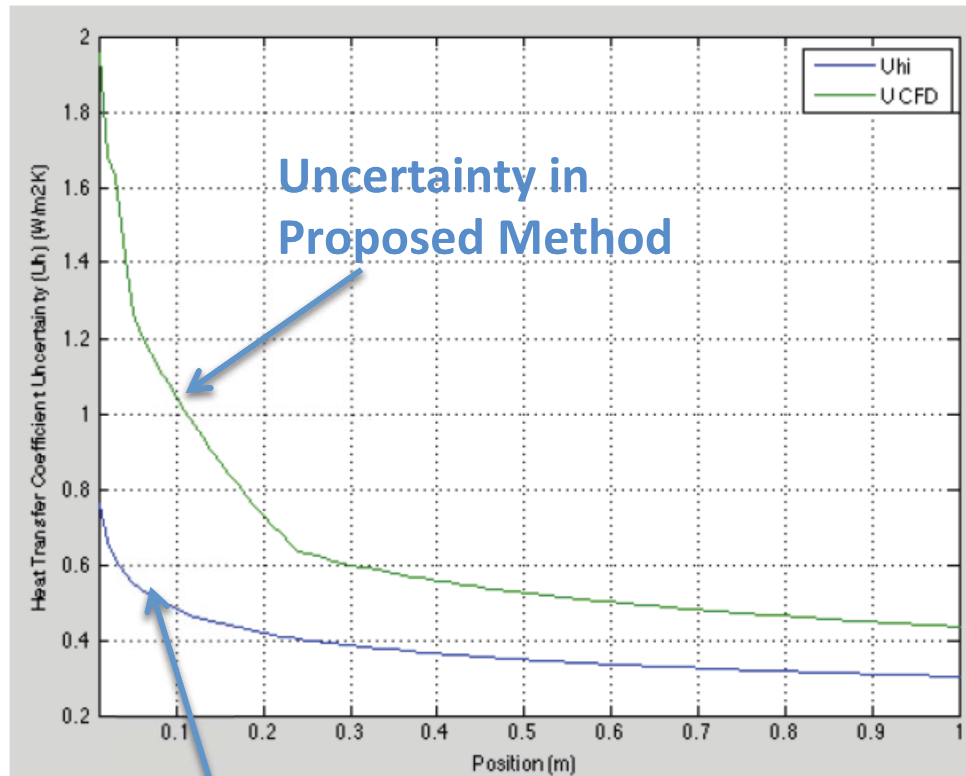
- Traditional vs. Proposed

Heat Transfer Coefficient



Uncertainty in Heat Transfer Coefficient



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Comparison of Methods

- Traditional vs. Proposed Average Heat Transfer Coefficient over Flat Plate

  – Traditional

  $$h_{avg} = 2.66 \text{ +/- } 0.74 \text{ [W/m2K]}$$

  – Proposed CFD,

  $$h_{avg} = 2.66 \text{ +/- } 1.39 \text{ [W/m2K]}$$

Conclusion

- Proposed Method Envelops the True value and uses only CFD Data to Estimate the Uncertainty for Heat Transfer over a Flat Plate
  - No Testing

- Proposed methodology can be used to conservatively estimate the uncertainty in CFD models

Chapter 6: Demonstration and Implementation of the Proposed CFD Uncertainty Method for Spacecraft ECS Systems

0.75m Configuration

3.5m Configuration

5.5m Configuration

ECS System Experimental Comparison

Spacecraft / ECS System

AIAA-2014-0440

Uncertainty Calculation

- Proposed Methodology

$S \pm u_{val}$

$$u_{val} = k\left(\sqrt{{u_{num}}^2 + {u_{input}}^2}\right)$$

Input Variable	Description	Bias
Grid	3 grids considered for each configuration	
Inlet Velocity	Boundary Condition low and high	10%
Outlet Pressure	Boundary Condition low and high	2%
Turbulence Model	SA, ke-realizable, kwSST	
Wall Functions	with and without	
Rough Wall Function	smooth vs. rough	
Compressibility	incompressible vs. compressible	
Solver	OpenFoam, Fluent, STARCCM+	
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05

- Expanding

$$u_{val} = k\left(\left(\left(\frac{\partial V}{\partial grid}\right)^2 B_{grid}^2\right) + \left(\left(\frac{\partial V}{\partial pressure}\right)^2 B_{pressure}^2\right) + \left(\left(\frac{\partial V}{\partial velocity}\right)^2 B_{velocity}^2\right) + \left(\left(\frac{\partial V}{\partial rho}\right)^2 B_{rho}^2\right)\right.$$
$$+ \left(\left(\frac{\partial V}{\partial wall\ functions}\right)^2 B_{wall\ functions}^2\right) + \left(\left(\frac{\partial V}{\partial surface\ roughness}\right)^2 B_{surface\ roughness}^2\right)$$
$$+ \left(\left(\frac{\partial V}{\partial compressibility}\right)^2 B_{compressibility}^2\right) + \left(\left(\frac{\partial V}{\partial solver}\right)^2 B_{solver}^2\right)$$
$$\left.+ \left(\left(\frac{\partial V}{\partial turbulence}\right)^2 B_{turbulence}^2\right)\right)^{1/2}$$

Uncertainty Calculation

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Case #	Parameter	Grid	Configuration 0.75	3.5	5.5
1		coarse	1	1	1
2		med	2	2	2
3		fine	3	3	3
	Boundary Conditions				
4		inlet velocity low	4	4	4
5		inlet velocity high	5	5	5
6		pressure outlet low	6	6	6
7		pressure outlet high	7	7	7
	Turbulence Models				
8		SA	8	8	8
9		ke-realizable - same as1	9	9	9
10		kwsst	10	10	10
11	Wall Functions	without wall functions	11	11	11
12	Surface Roughness	rough wall function	12	12	12
13	Compressibility	different openfoam solver	13	13	13
	Solver				
14		fluent	14	14	14
15		starccm	15	15	15
	Fluid Properties				
16		nut high	16	16	16
17		nut low	17	17	17

Number of Cases	Degrees of Freedom	Confidence 90%
2	1	6.314
3	2	2.92
4	3	2.353
5	4	2.132
6	5	2.015
7	6	1.943
8	7	1.895
9	8	1.86
10	9	1.833
11	10	1.812
12	11	1.796
13	12	1.782
14	13	1.771
15	14	1.761
16	15	1.753
17	16	1.746
18	17	1.74
19	18	1.734
20	19	1.729
21	20	1.725
22	21	1.721
23	22	1.717
24	23	1.714
25	24	1.711
26	25	1.708
27	26	1.706
28	27	1.703
29	28	1.701
30	29	1.699
31	30	1.697
41	40	1.684
51	50	1.676
61	60	1.671
81	80	1.664
101	100	1.66
121	120	1.658
infty	infty	1.645

$$u_{val} = 1.746 * \left|\frac{1}{2}(S_U - S_L)\right|$$

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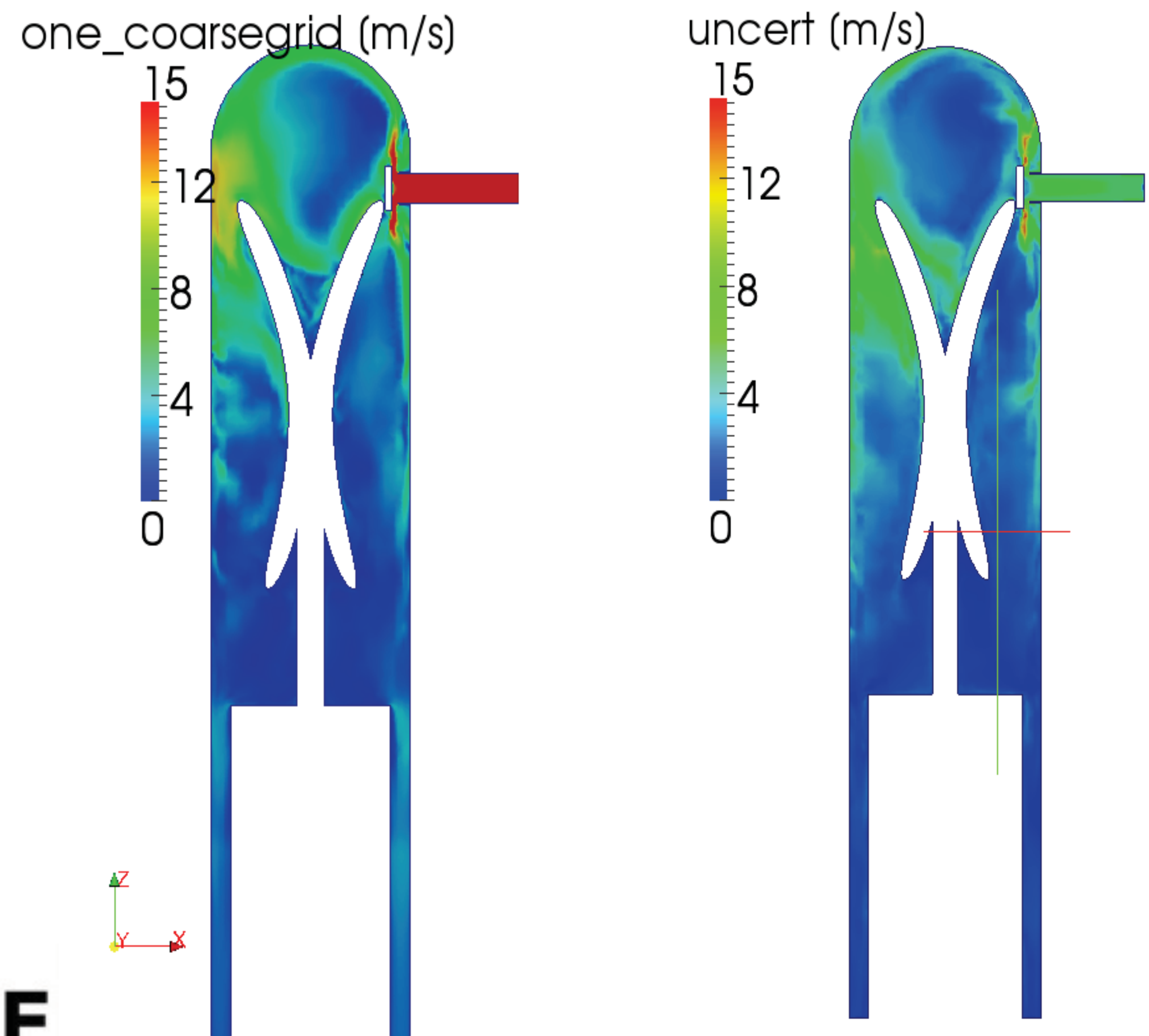
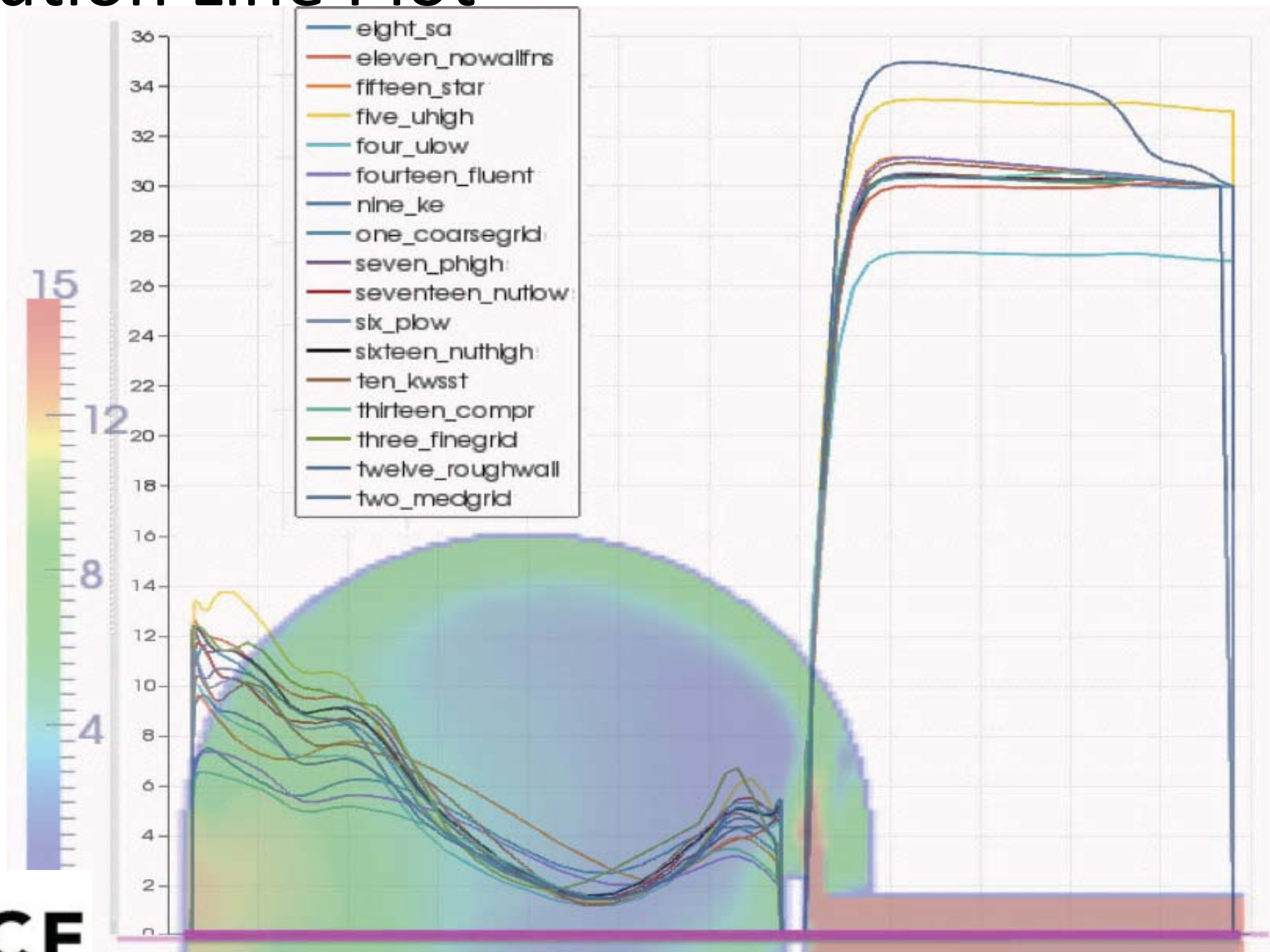
Results 0.75m Configuration

- Solution and Uncertainty Contour Plots



Results 0.75m Configuration

- Solution Line Plot



Results 0.75m Configuration

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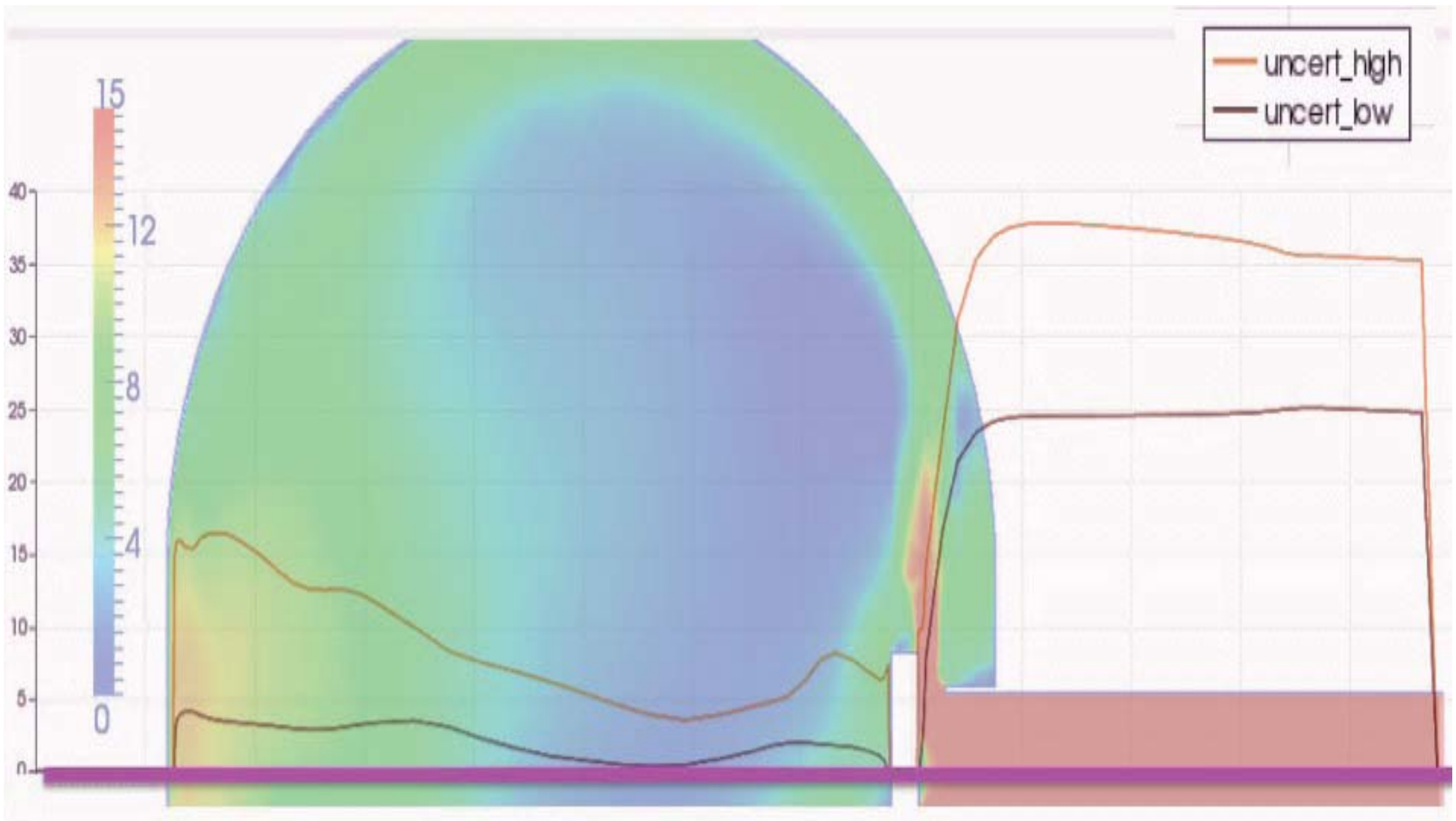
- Uncertainty Line Plot



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Results 0.75m Configuration

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- ## Uncertainty Ranking

- The uncertainty for each of the input variables were ranked by the non-dimensionalizing the difference in the results by the freestream value and ranking from greatest uncertainty to least uncertainty.

Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		1.6287	0.0543	13.40	2
Inlet Velocity	Boundary Condition	10%	1.3115	0.04737	11.69	5
Outlet Pressure	Boundary Condition	2%	1.1478	0.0383	9.45	8
Turbulence Model	SA, ke-realizable, kwSST		1.4628	0.0488	12.04	4
Wall Functions	with and without		0.8286	0.0276	6.81	9
Rough Wall Function	smooth vs. rough		1.5237	0.0508	12.53	3
Compressibility	incompressible vs. compressible		1.3128	0.0438	10.81	6
Solver	OpenFoam, Fluent, STARCCM+		1.673	0.0558	13.77	1
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	1.1536	0.0385	9.50	7

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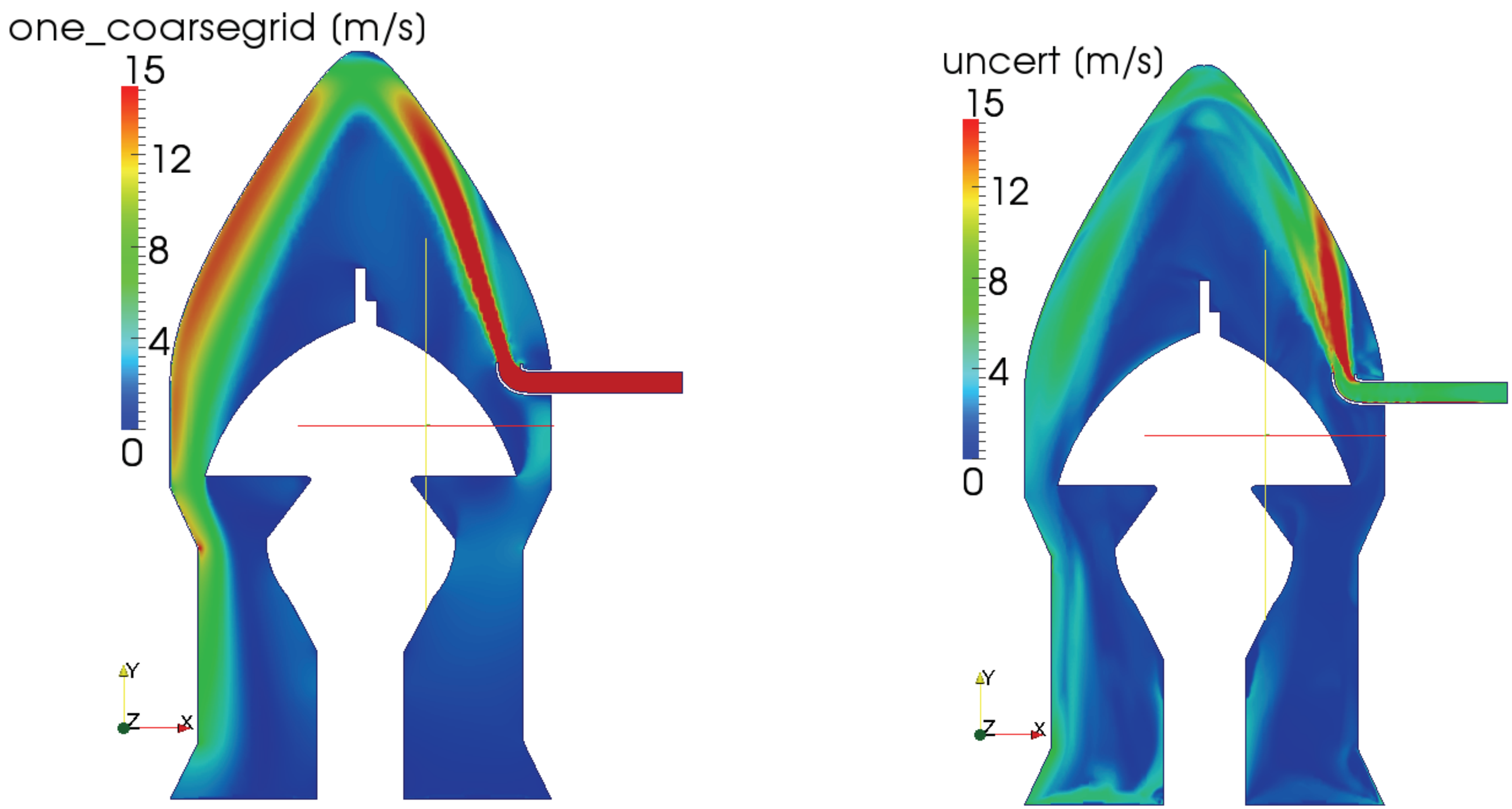
Results 3.5m Configuration

- Solution and Uncertainty Contour Plots



Results 3.5m Configuration

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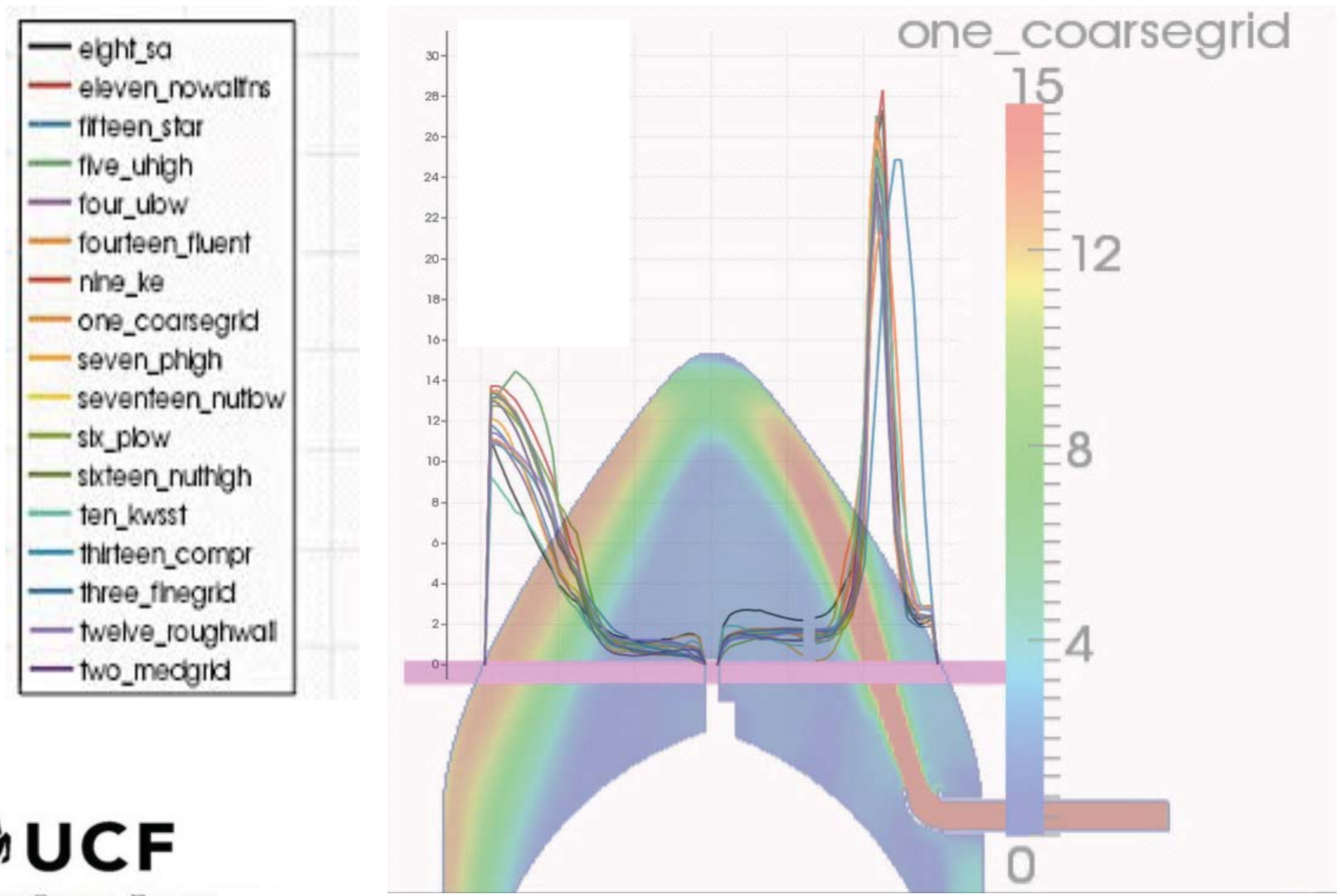
- Solution Line Plot



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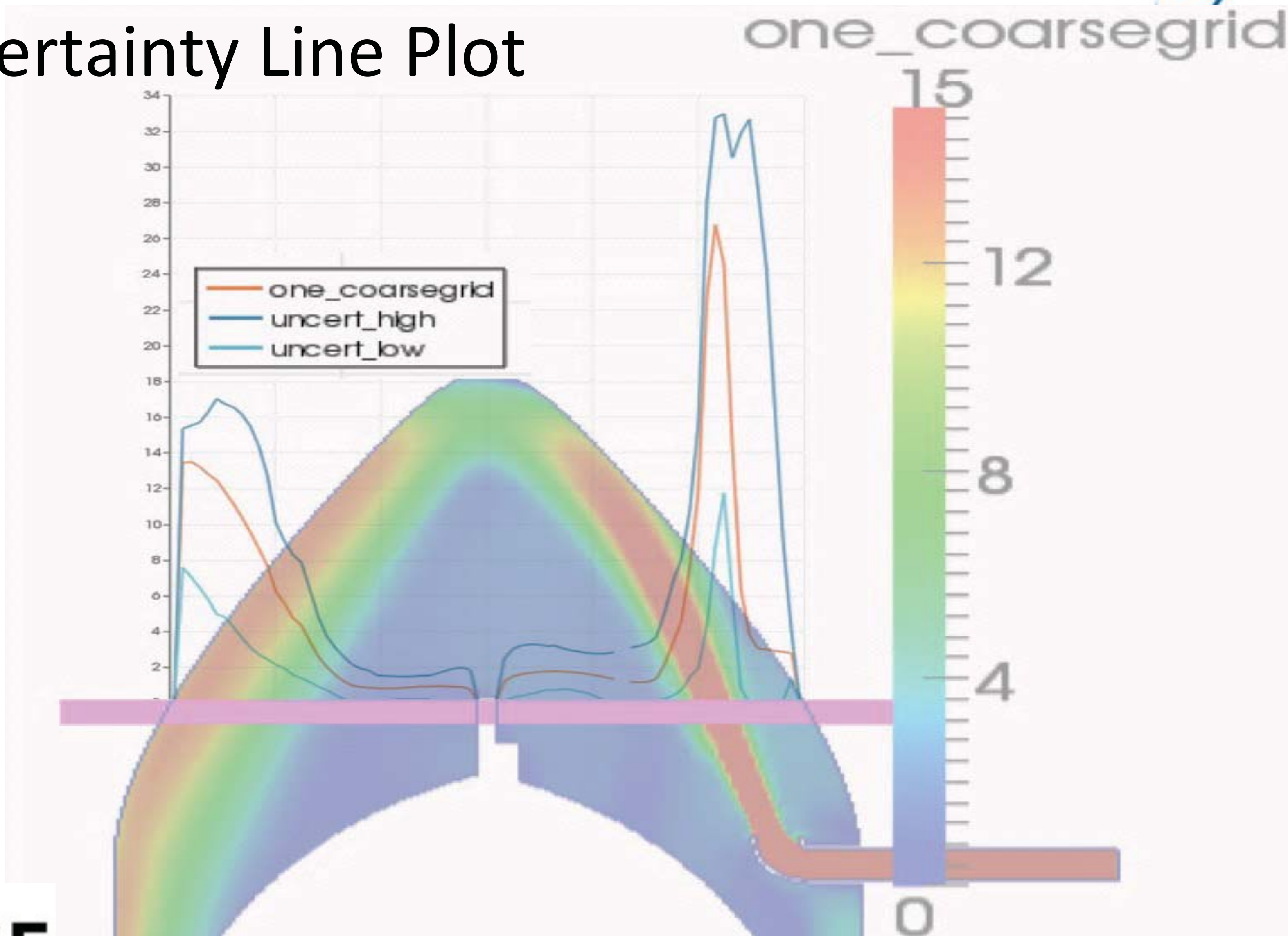
Results 3.5m Configuration

- Uncertainty Line Plot



Results 3.5m Configuration

- Uncertainty Ranking

Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		0.6829	0.0228	8.28	7
Inlet Velocity	Boundary Condition	10%	0.7919	0.0264	9.59	6
Outlet Pressure	Boundary Condition	2%	1.4606	0.0487	17.70	1
Turbulence Model	SA, ke-realizable, kwSST		1.3487	0.045	16.35	2
Wall Functions	with and without		0.6139	0.0205	7.45	9
Rough Wall Function	smooth vs. rough		1.0531	0.0351	12.75	3
Compressibility	incompressible vs. compressible		0.8252	0.0275	9.99	5
Solver	OpenFoam, Fluent, STARCCM+		0.841	0.028	10.17	4
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	0.6345	0.0212	7.70	8

Results 5.5m Configuration

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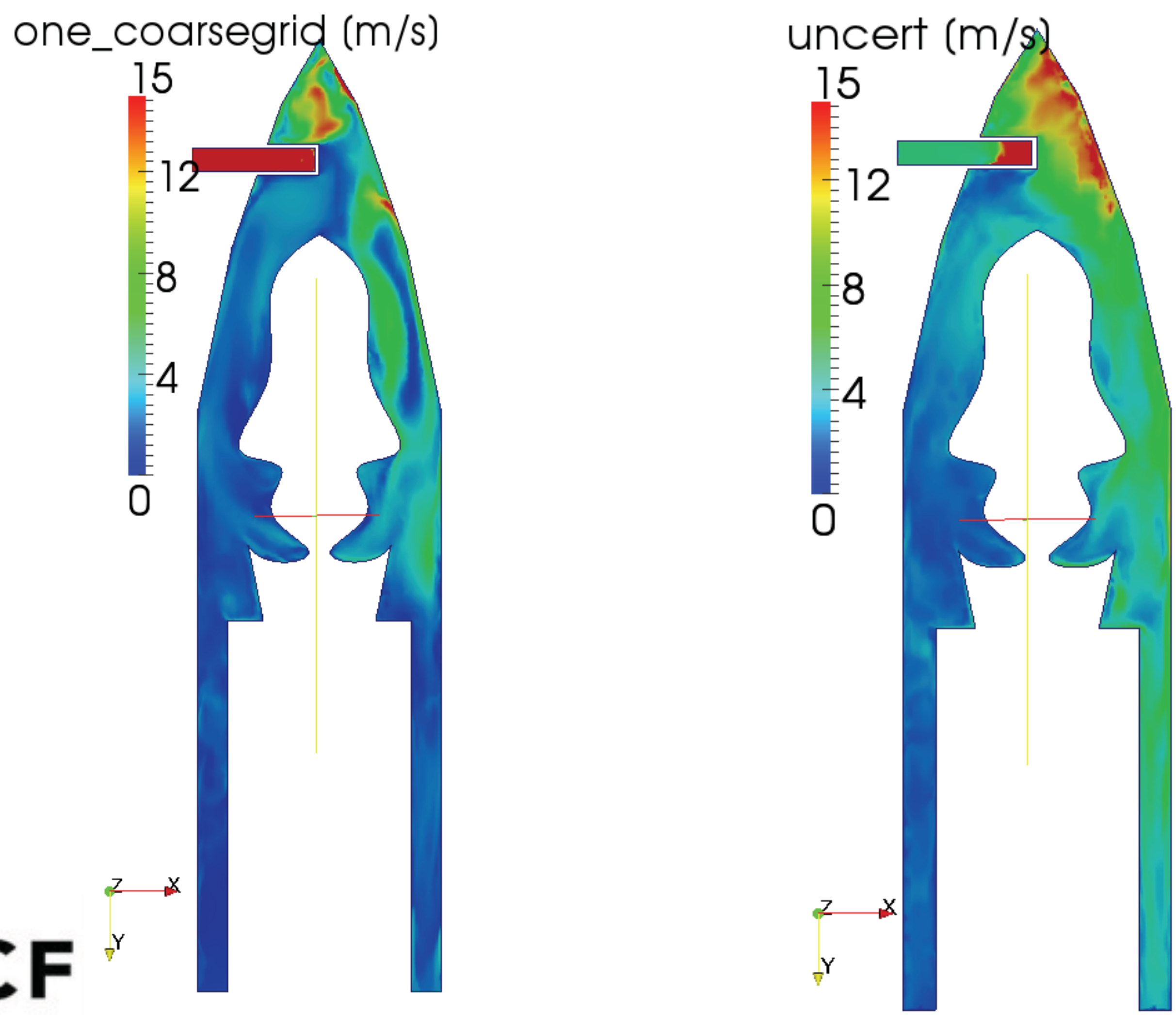
- Solution and Uncertainty Contour Plots



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Results 5.5m Configuration

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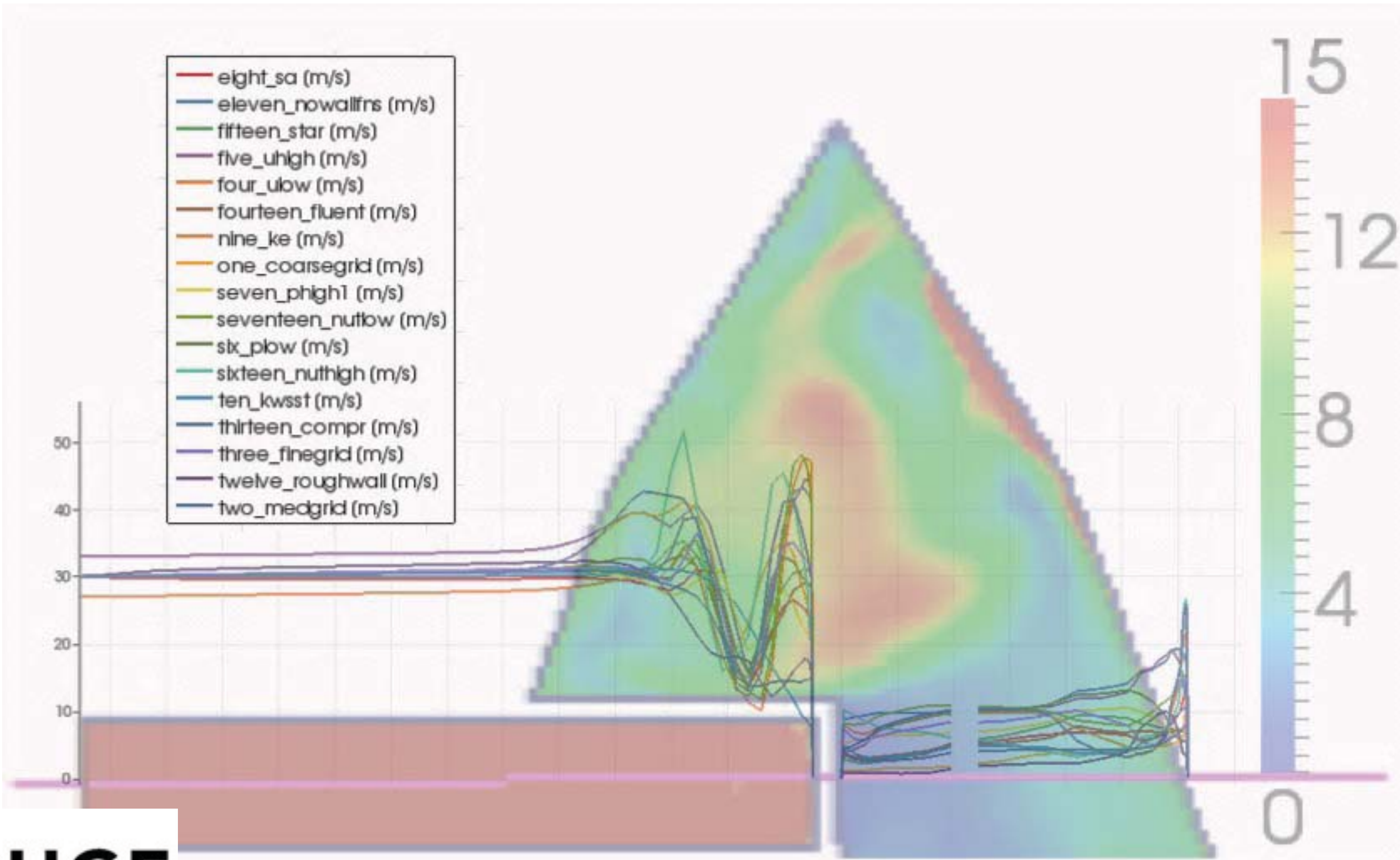
- Solution Line Plot



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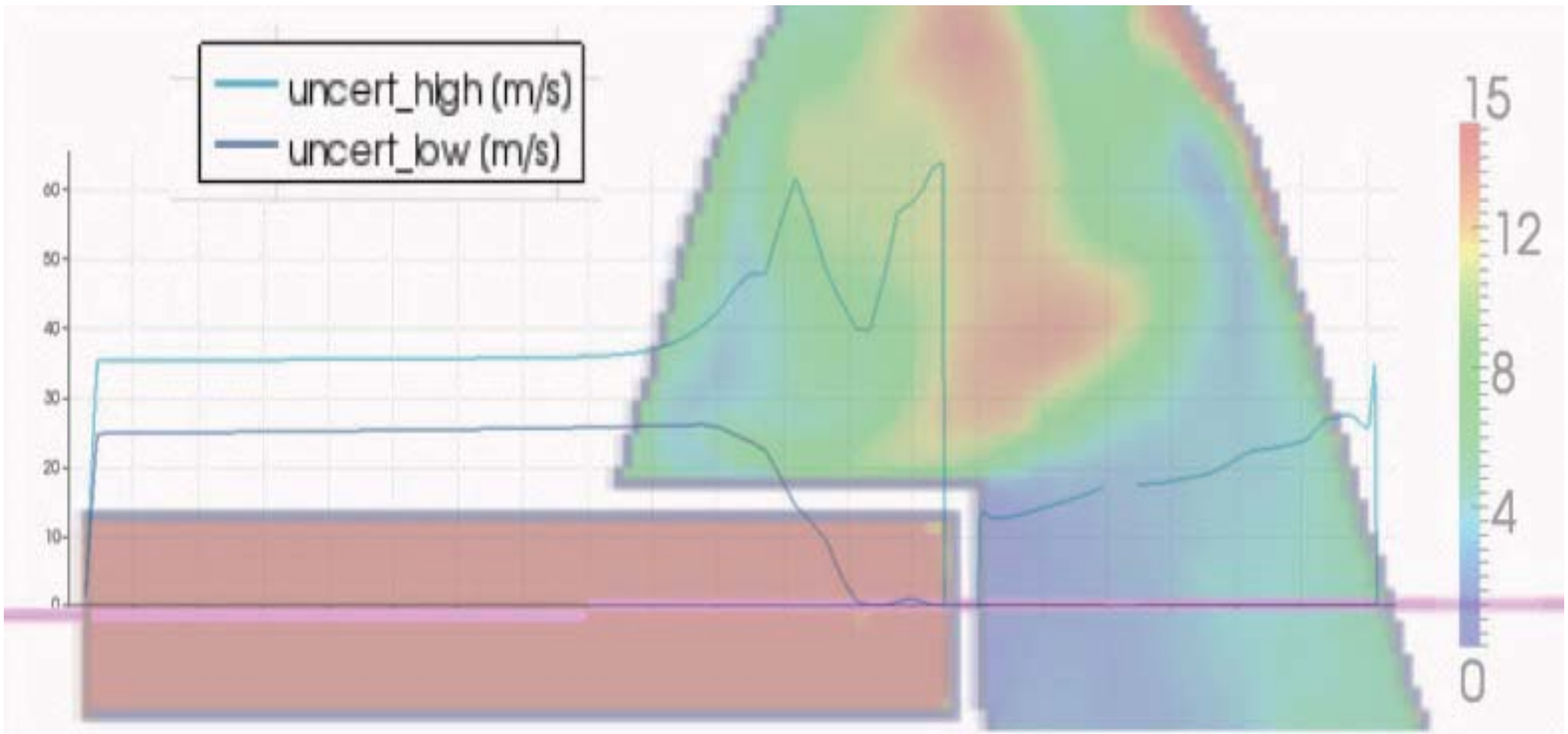
Results 5.5m Configuration

- Uncertainty Line Plot



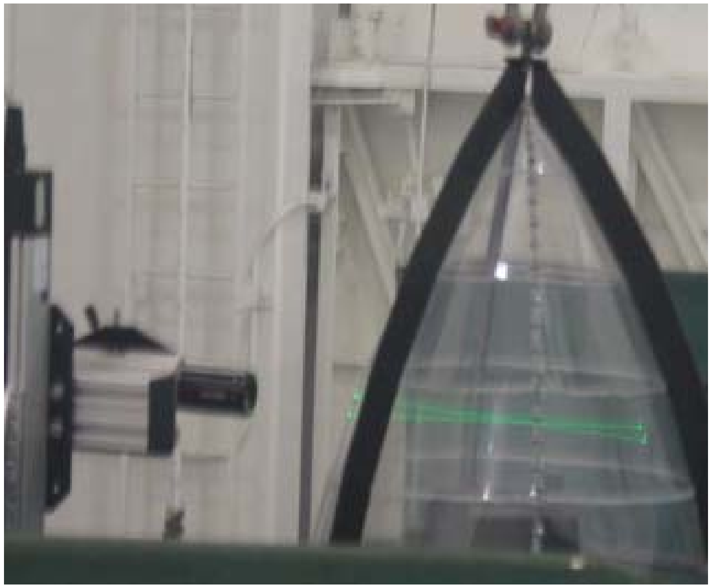
Results 3.5m Configuration

- Uncertainty Ranking

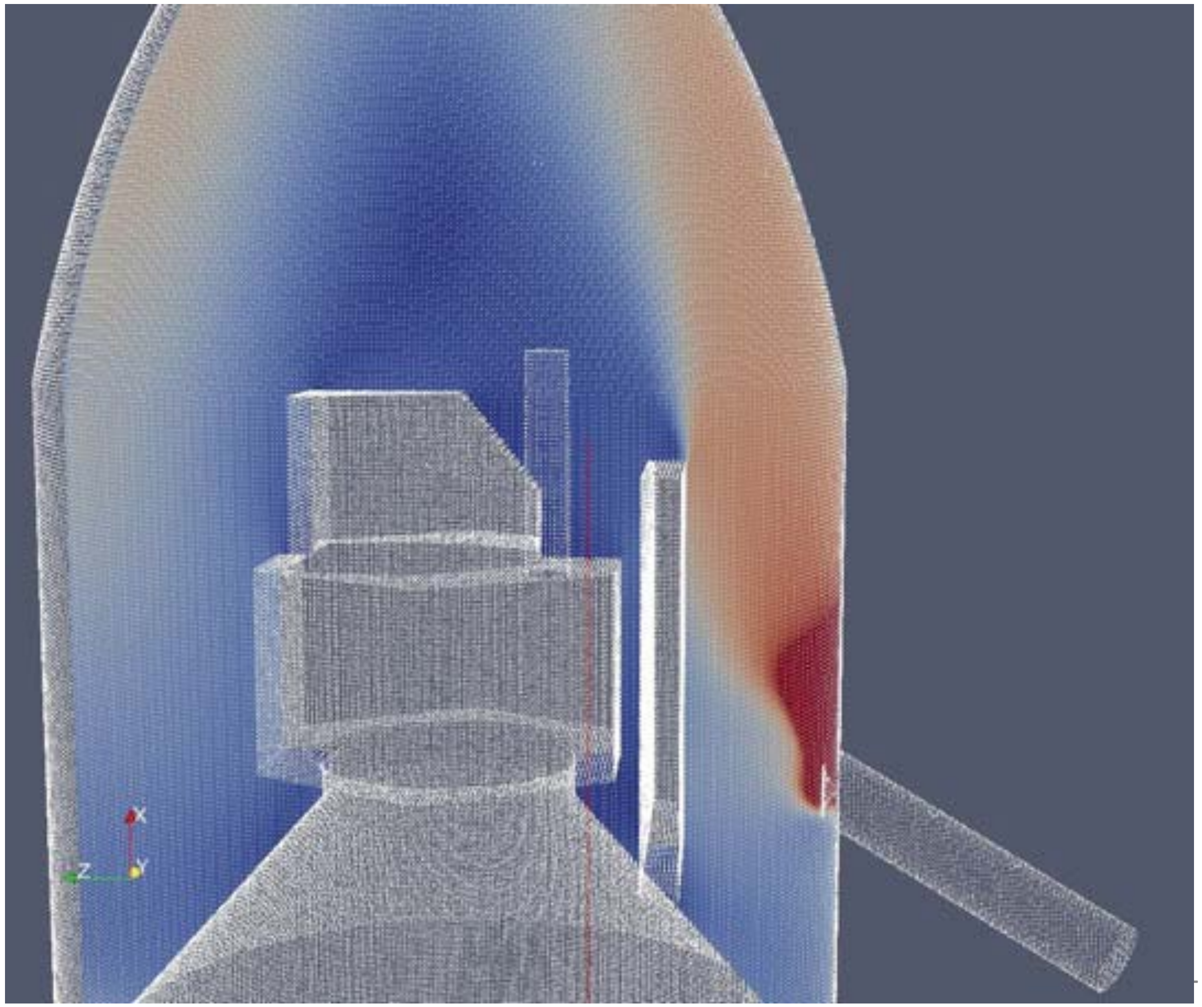
Input Variable	Description	Bias	Mean Velocity Uncertainty (m/s)	Mean Non-Dimensionalized Uncertainty	Normalized Ranking %	Numbered Ranking
Grid	3 grids considered		2.0203	0.0673	12.44	3
Inlet Velocity	Boundary Condition	10%	1.6198	0.054	9.98	6
Outlet Pressure	Boundary Condition	2%	2.0173	0.0672	12.42	4
Turbulence Model	SA, ke-realizable, kwSST		2.3049	0.0768	14.19	1
Wall Functions	with and without		1.4902	0.0497	9.18	7
Rough Wall Function	smooth vs. rough		1.4901	0.0497	9.18	8
Compressibility	incompressible vs. compressible		1.4256	0.0475	8.78	9
Solver	OpenFoam, Fluent, STARCCM+		1.8172	0.0606	11.20	5
Fluid Properties	kinematic viscosity nu represents air [0-50-100] deg C	1.36,1.5,2.306e-05	2.05	0.0683	12.62	2

Comparison to Previous LDV Test

Variable	Bias
Velocity Inlet	3%
Kinematic Viscosity [0-100] Deg C	[1.36, 1.50, 2.306] e-5 m2/s
Pressure Outlet	3%
Turbulence	ke-realiazable, kwsst, SA



Kandula, M., Hammad, K., and Schallhorn, P., "CFD Validation with LDV Test Data for Payload/Fairing Internal Flow," AIAA-2005-4910, 2005.



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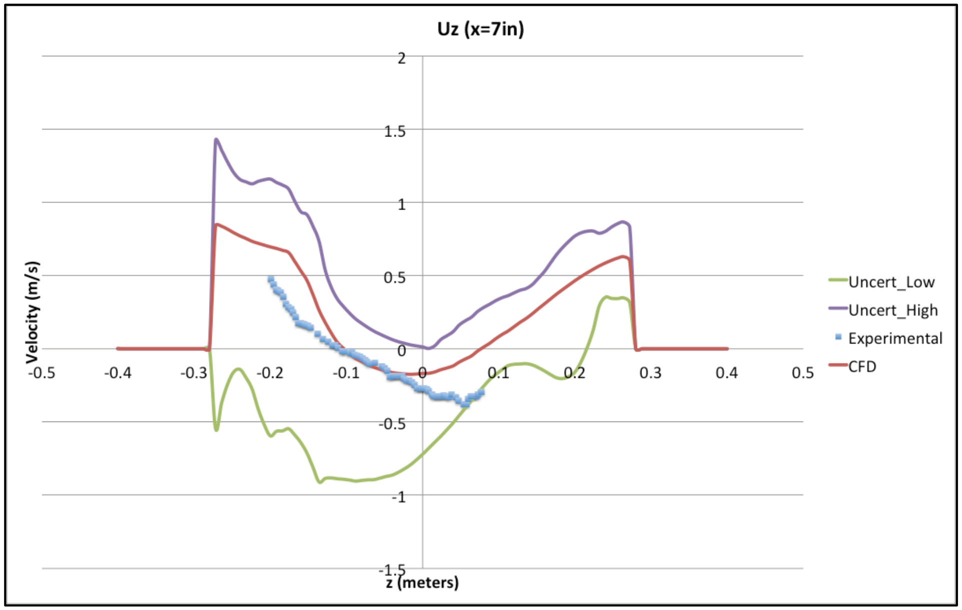
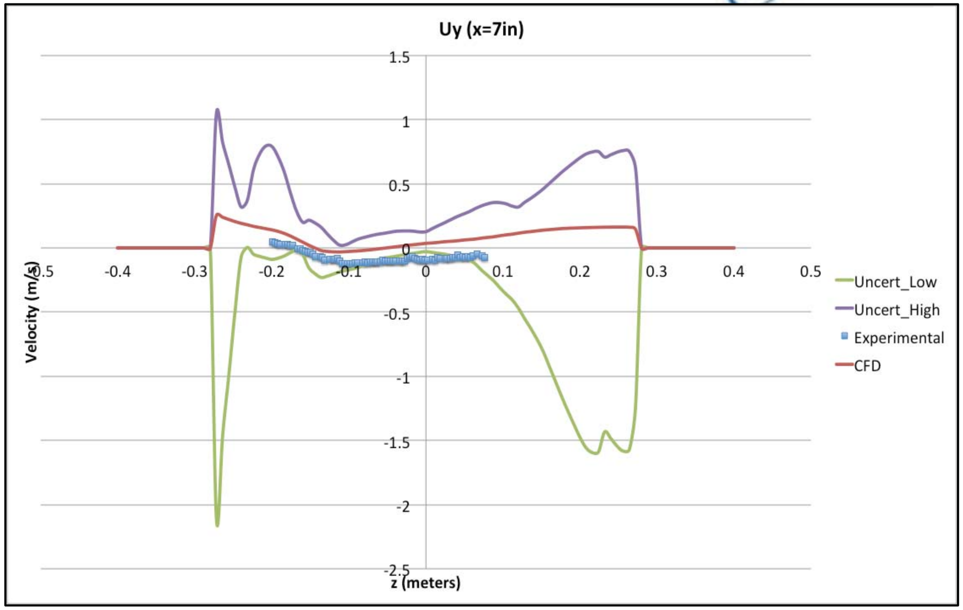
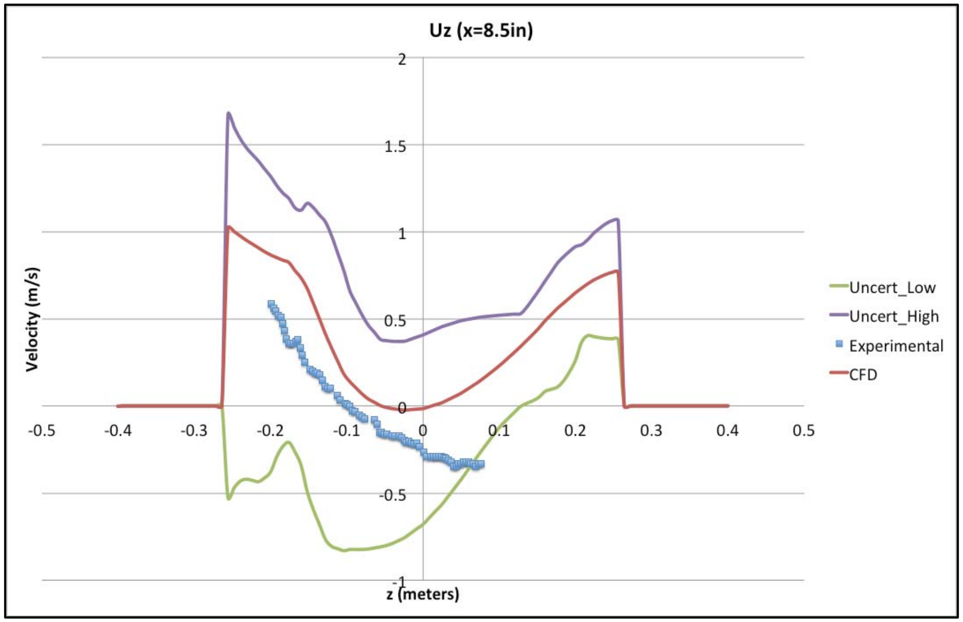
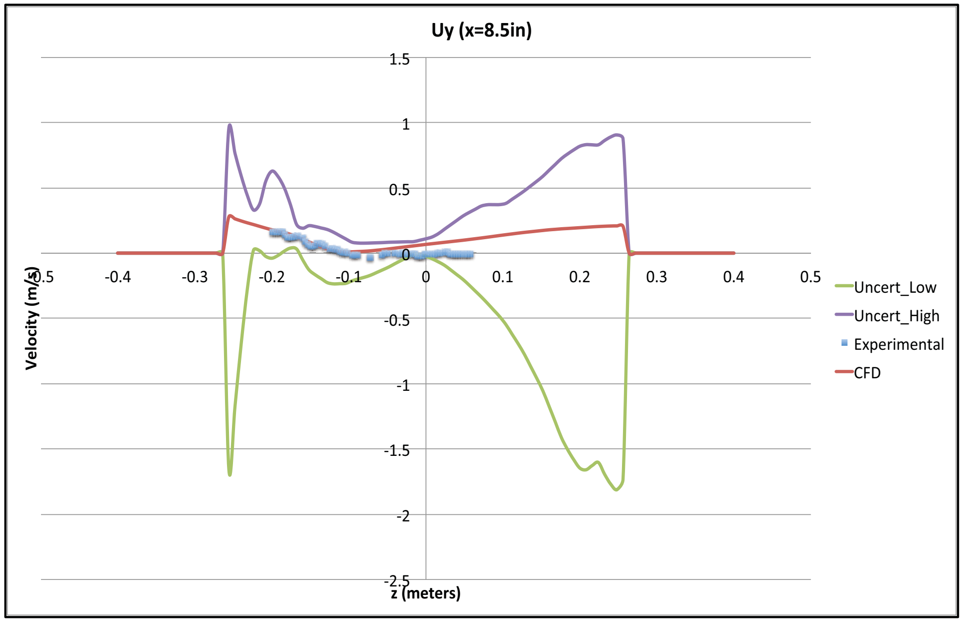
Comparison to Previous LDV Test

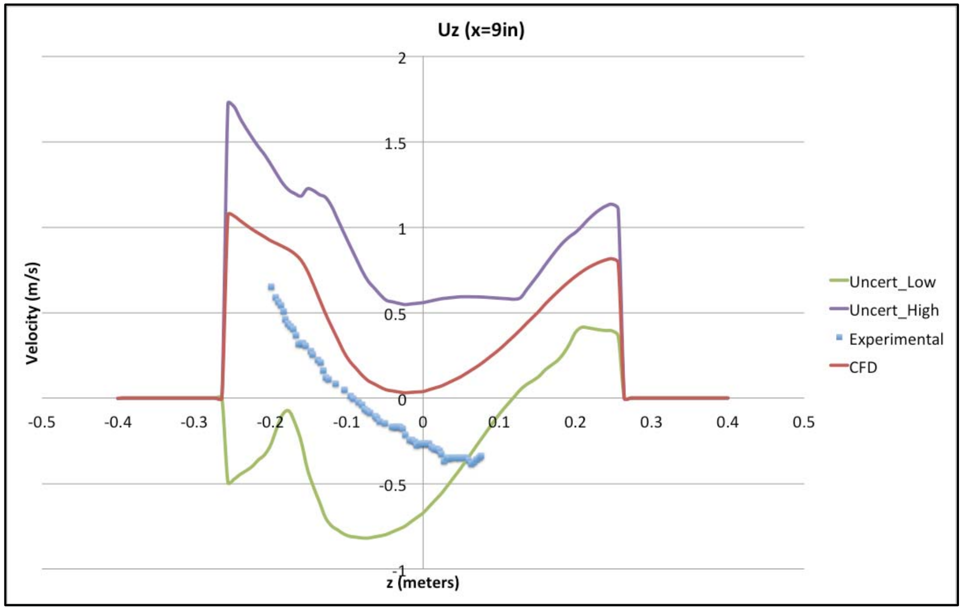


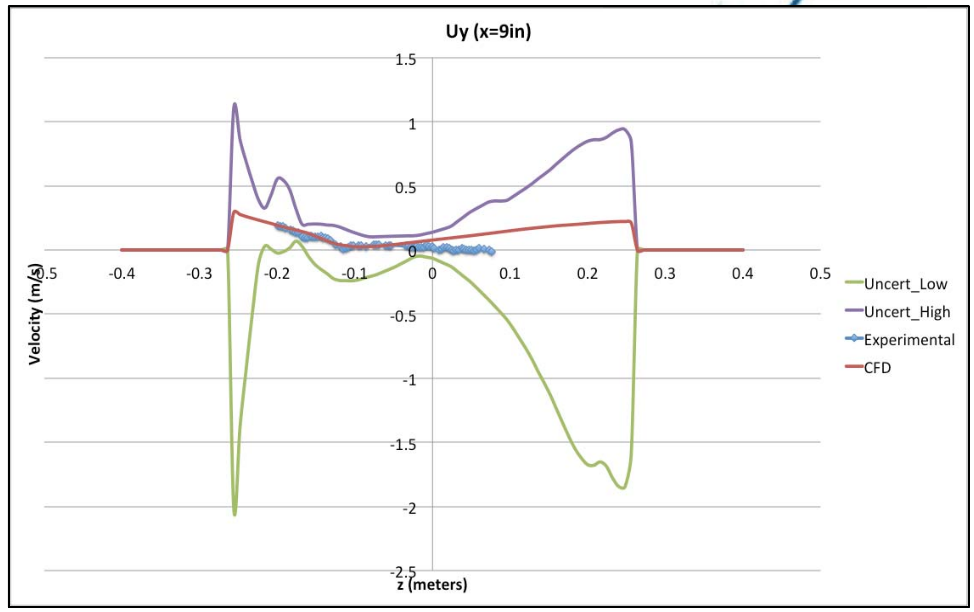


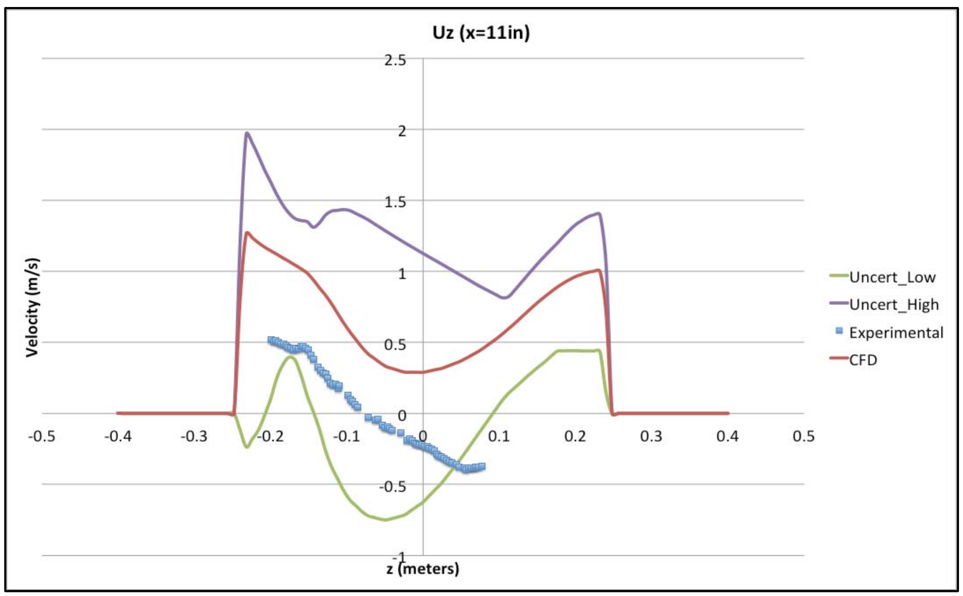


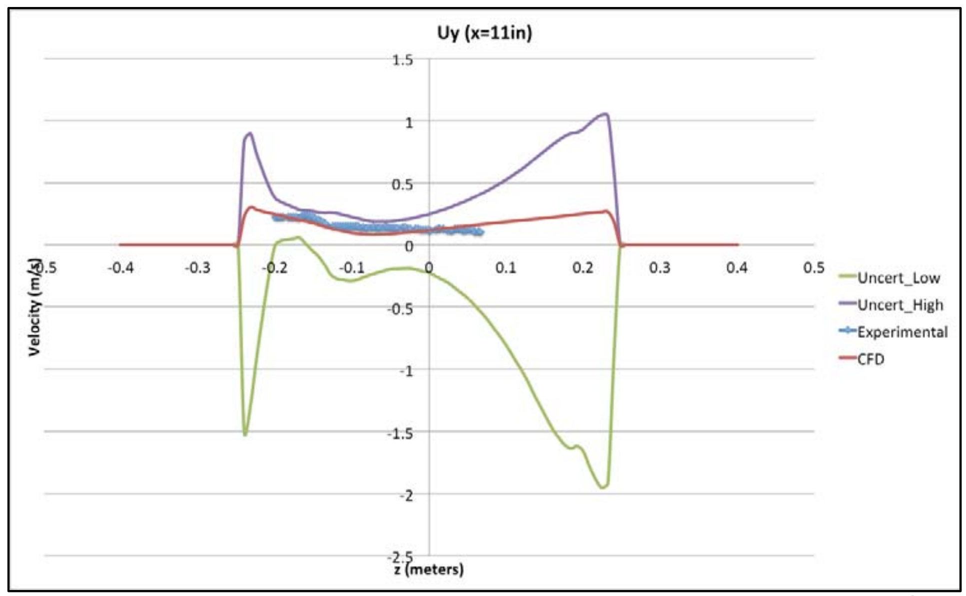


Comparison to Previous LDV Test

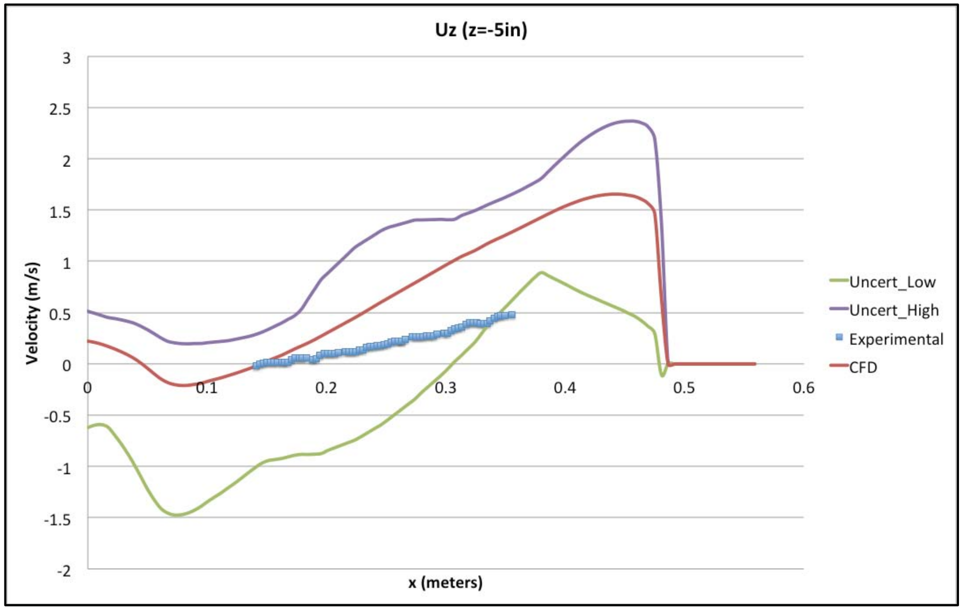


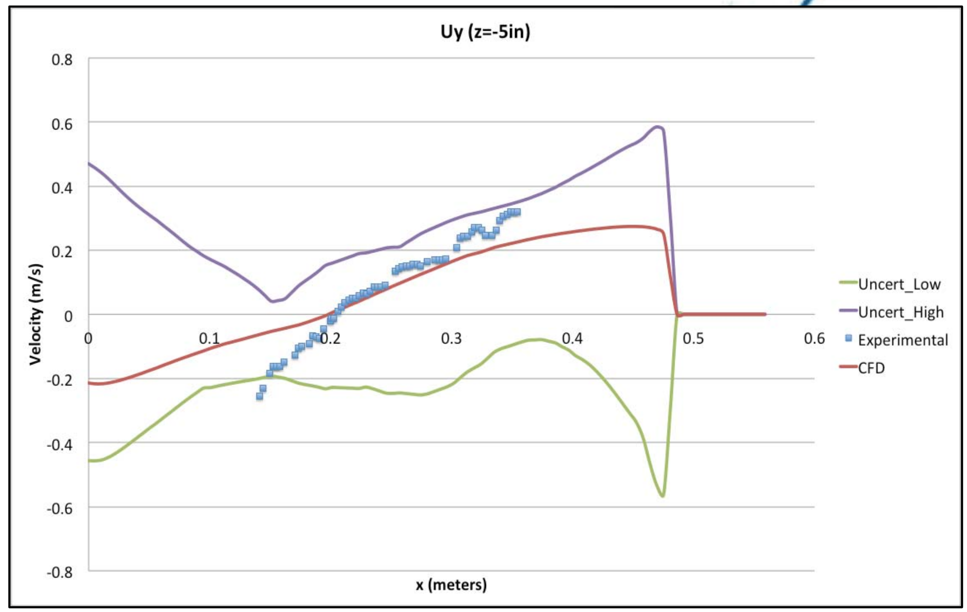


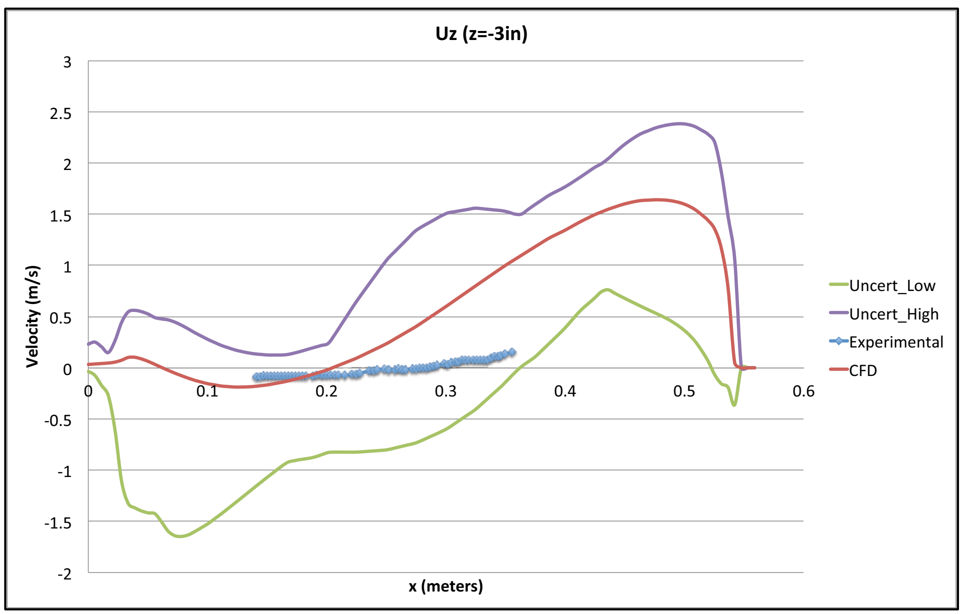


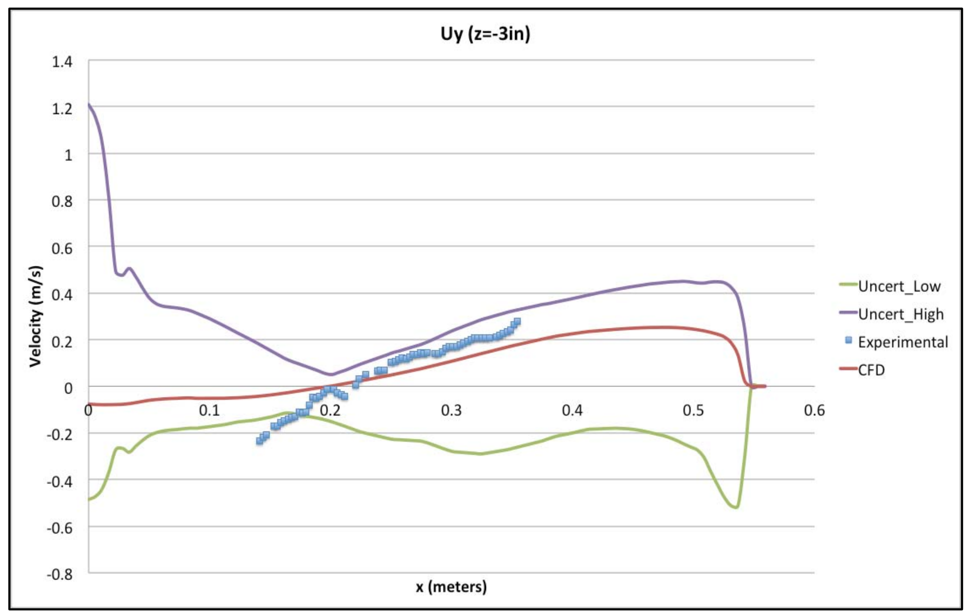


Comparison to Previous LDV Test

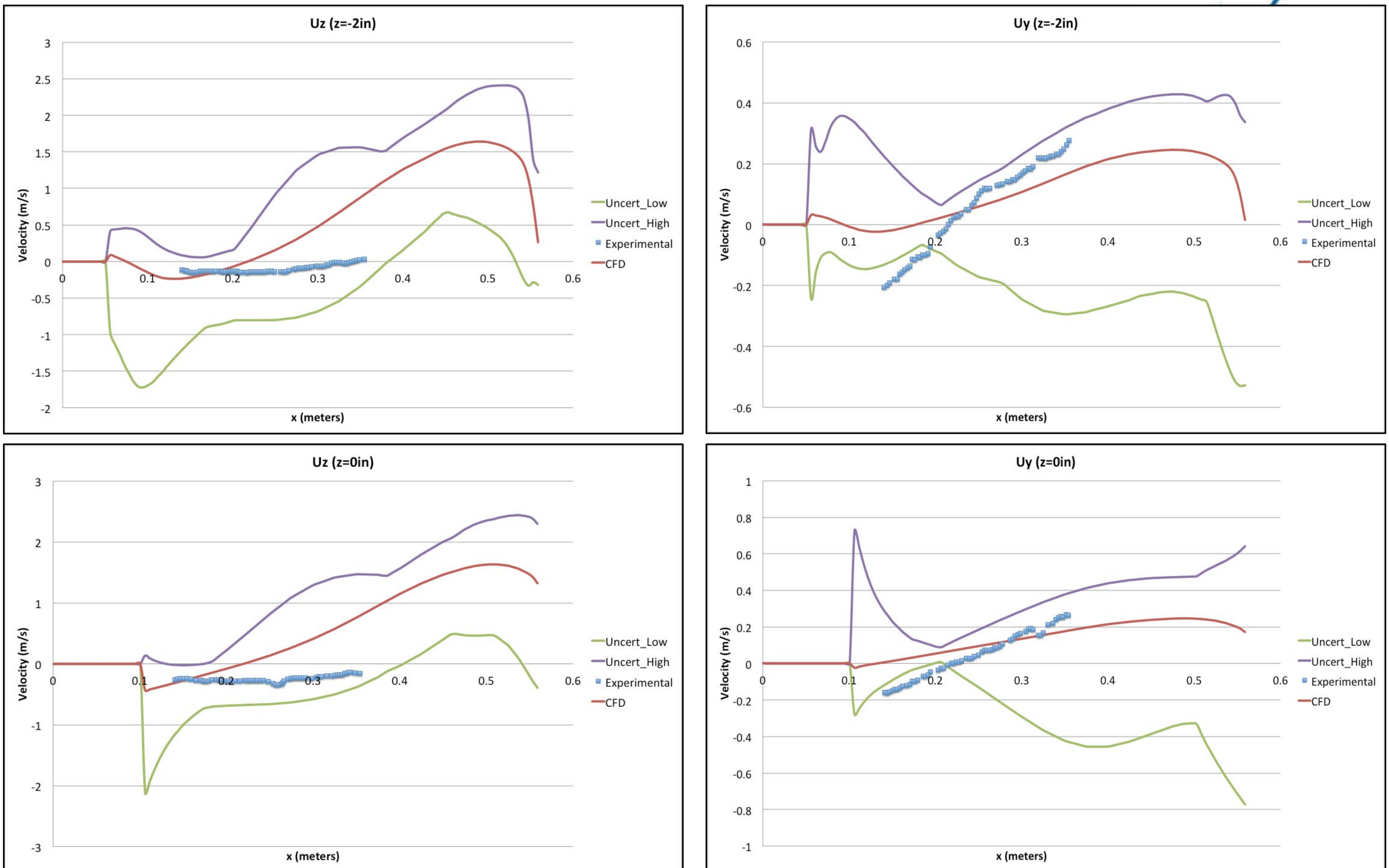








Comparison to Previous LDV Test



Comparison to Previous LDV Test

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LAUNCH SERVICES PROGRAM

- Assumed Confidence Interval from Student T distribution and CFD Uncertainty Prediction
  - 90%
- LDV Data
  - Total of 1085 Points Measured
  - 977 Points were inside the 90% CFD Uncertainty Methodology
  - 108 Points Outside CFD Uncertainty Prediction
    - 977/1085 = 0.90046
    - ~90%

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AIAA-2014-0440 Conclusion & Recommendation

- Proper validation with experimental data should be used to verify ECS impingement requirements
- This research proposes a CFD uncertainty methodology when experimental data is unavailable and unobtainable
  - Couples Student-T Distribution to the number of CFD models and input parameters
  - All input parameters considered had the same order of magnitude uncertainty

Chapter 7: Conclusions and Future Work

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Conclusion & Recommendation

LAUNCH SERVICES PROGRAM

- Proper validation with experimental data should be used when possible
- This research proposes a CFD uncertainty methodology when experimental data is unavailable and unobtainable
  - Couples Student-T Distribution to the number of CFD models and input parameters
  - Methodology proved accurate for:
    - Fully Developed Laminar Flow between Parallel Plates
    - Heat Transfer over a Flat Plate
    - Spacecraft / Fairing Environmental Control Systems

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Future Work

- Run Experimental Configurations to further prove methodology
  - Evaluate which models are most realistic
  - Try to reduce conservatism in proposed methodology (if possible)
- Expand Method beyond internal, low-speed, incompressible
  - Other Flow Regimes: External, Compressible, Unsteady
  - Expand Beyond Fluid Dynamics and Heat Transfer

Summary

- "Uncertainty (of measurement) – parameter, associated with the result of a measurement, that characterizes the dispersion of values that could be reasonably attributed to the the quantity intended to be measured" – International Vocabulary of Basic and General Terms in Metrology

- Replace
  - Measurement –> Simulation
  - Measured -> Simulated

Thank You

- Chair: Dr. Alain Kassab

- Committee Members
  - Dr. Tuhin Das
  - Dr. Jeffrey Kauffman
  - Dr. Brian Moore

- NASA, Launch Services Program
  - Dr. Paul Schallhorn
  - Lennie Duncil
  - Larry Craig